NASA CONTRACTOR REPORT

NASA CR-179225

CARBON DIOXIDE OBSERVATIONAL PLATFORM SYSTEM (CO-OPS) FEASIBILITY STUDY

By D. L. Bouquet, D. W. Hall, R. P. McElveen
Lockheed-Georgia Company
Marietta, GA 30063

Final Report

December 1987

Prepared for
NASA-Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-179225		

4. Title and Subtitle	5. Report Date
CARBON DIOXIDE OBSERVATIONAL PLATFORM SYSTEM (CO-OPS) Feasibility Study	December 1987
	6. Performing Organization Code
7. Author(s) D.L. Bouquet, D. W. Hall, R. P. McElveen	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address Lockheed-Georgia Company Marietta, GA 30063	11. Contract or Grant No. NAS8-36600
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	13. Type of Report and Period Covered Contractor Report Final
	14. Sponsoring Agency Code

15. Supplementary Notes

Contract Monitor, Wilbur E. Thompson, Program Development, Marshall Space Flight Center

16. Abstract The Carbon Dioxide Observational Platform System (CO-OPS) is a near-space, geo-stationary, multi-user, unmanned microwave powered monitoring platform system. It could potentially operate continuously for periods of up to 3 months in quasi-fixed position over regional targets of interest and could make horizon observations over a land-sea area of circular diameter up to about 600 to 800 statute miles. This affords the scientific and engineering community a low-cost means of operating their payloads for monitoring the regional parameters they deem relevant to their investigations and operations at one-tenth the cost of most currently utilized comparable remote sensing techniques.

This systems engineering feasibility study addressed clearly identified existing requirements such as the: (1) carbon dioxide observational data requirements, (2) communications requirements, and (3) eye-in-the-sky requirements of other groups like the Defense Department, the Forestry Service, and the Coast Guard. In addition, potential applications in: (1) Earth System Science, (2) Space System Sciences, and (3) Test and Verification (Satellite Sensors and Data Management Techniques) were considered.

This report is a primary technical reference for: "System Study of the Carbon Dioxide Observational Platform System (CO-OPS): Project Overview." NASA Technical Paper 2696, March 1987.

This report summarizes an eleven-month effort on the part of Lockheed-Georgia Company and its subcontractors Raytheon, Ball Aerospace and Sundstrand, to study feasibility of CO-OPS. Past work and methods of gathering the required observational data were assessed and rough-order-of magnitude cost estimates have shown the CO-OPS system to be most cost-effective (less than $30 million dollars with a 10-year life-time). The study team also concluded that there are no technical, schedule or cost obstacles that would prevent achieving the objectives of the total 5-year CO-OPS program.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Remote Sensing Atmospheric Models Aeronautics Microwave Power	Unclassified--Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	207	NTIS

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

TABLE OF CONTENTS

Section		Page
	EXECUTIVE SUMMARY	1
1.0	INTRODUCTION	27
	1.1 Background	27
	1.2 The Concept of Microwave Powered Flight	28
	1.3 The Purpose of This Investigation	32
	1.4 Scope	32
2.0	TECHNICAL APPROACH	33
	2.1 Systems Engineering	33
	2.2 Subsystem Interactions	33
3.0	REQUIREMENTS DEFINITION	36
	3.1 Overview	36
	3.2 Discussion of Observational Data Requirements for Each Site	37
	3.3 Some Interactions of Subsystem Design Requirements	39
	3.4 System Mobility Requirements	41
	3.5 Flight Controls Requirements	41
4.0	PAYLOAD SUBSYSTEM	42
	4.1 Overview	42
	4.2 Effect of State-of-the-Art on Choice of Payload Package	44
	4.3 Selection of A Typical Payload Complement	44
	4.4 Characterization of Payload Subsystem Options	47
5.0	PLATFORM SUBSYSTEM SIZING METHODOLOGY	57
	5.1 Overview	57
	5.2 Candidate Configurations	57
	5.3 Aerodynamic Characterization of Platforms	59
	5.4 Structural Mass Estimation	62
	5.5 Interfaces	63
	5.6 Life Cycle Cost Model for the Platform	65
	5.7 Results	67
6.0	GROUND POWER AND PROPULSION SUBSYSTEM	70
	6.1 Overview	70
	6.2 Atmospheric Environment	71
	6.3 Ground Power Subsystem Characterization	78
	6.4 Airborne Rectenna Characterization	104
	6.5 Airborne Thrust Generation Characteristics	107

PRECEDING PAGE BLANK NOT FILMED

TABLE OF CONTENTS
(Cont'd)

Section			Page
7.0	DATA SUBSYSTEM		113
	7.1	Overview	113
	7.2	Control Functions	115
8.0	SYSTEMS ENGINEERING AND INTEGRATION		121
	8.1	Overview	121
	8.2	System Sizing Methodology	123
	8.3	Subsystem Interactions	140
	8.4	System Optimization	146
	8.5	Study Technical Results	153
	8.6	Integrated System Description	153
9.0	OPERATIONS AND MAINTENANCE		162
	9.1	Overview	162
	9.2	Mission Timeline	162
	9.3	Scheduled Maintenance	165
	9.4	Summary of System O & M Requirements	165
10.0	CONCLUDING REMARKS		169
	10.1	Viable Systems and Initial Operational Capability Options	169
	10.2	Issues Requiring Further Consideration	174
	10.3	Other Applications (Task 10)	180
	10.4	Recommendations (Task 9)	181
REFERENCES			182
APPENDIX: OBSERVATIONAL DATA REQUIREMENTS			186

Lockheed

LIST OF FIGURES

Figure	Title	Page
1	Observational Platforms	2
2	Parametric Convergence	5
3	Generic Configurations	12
4	Altitude Options	23
5	The Relationships of High Altitudes To Very Long Endurance	30
6	Historical Ranges of Power Loading and Wing Loading	31
7	A Schematic of the System Engineering Used	34
8	Payload Subsystem Study Plan	43
9	Summary of the Instrument Data Base Considered During This Study	45
10	Key Payload Subsystem Issues Affecting the CO-OP System	52
11	Preventing Deteriorative Effects of the Microwave Environment	52
12	Typical Platform Configuration With Disk-Mounted Rectenna	60
13	Typical Platform Configuration With Wing-Mounted Rectenna	60
14	Typical Joined Wing Configuration With Wing Mounted Rectenna	61
15	Comparison of Power Train Options for a CO-OPS Mission	72
16	Platform Design Cruise Airspeed Lower Limit Based On Worst Case Winds Aloft For Six Sites	72
17A	January Scalar Winds Aloft Over Nashville, Tenn.	74
17B	July Scalar Winds Aloft Over Nashville, Tennessee	74
18A	January Scalar Winds Aloft Over Vandenberg AFB, CA	74

LIST OF FIGURES (Cont'd)

Figure	Title	Page
18B	July Scalar Winds Aloft Over Vandenberg AFB, CA	74
19A	January Scalar Winds Over New York City, NY	75
19B	July Scalar Winds Aloft Over New York City, NY	75
20A	January Scalar Winds Aloft Over McMurdo Sound, Antarctica	75
20B	July Scalar Winds Aloft Over McMurdo Sound, Antarctica	75
21A	January Scalar Winds Aloft Over San Andreas Island, Colombia	76
21B	July Scalar Winds Aloft Over San Andreas Island, Colombia	76
22A	January Scalar Winds Aloft Over Frobisher Bay, Northwest Territory, Canada	76
22B	July Scalar Winds Aloft Over Frobisher Bay, Northwest Territory, Canada	76
23A	Summary Worst Case January Scalar Winds Aloft For All Six Sites	77
23B	Summary Worst Case July Scalar Winds Aloft For All Six Sites	77
24	Simplified System Block Diagram	79
25	Ground System	81
26	Slotted Array Configuration	84
27	11-Meter Disk Antenna	85
28	Ground Transmitter Magnetron Candidate	88
29	Ground Transmitter Amplifier Candidate	88
30	Magnetron Anode Current - Milliamperes	91
31	Frequency Change - Megahertz	92
32	Driver Frequency Change - MHZ	93

LIST OF FIGURES (Cont'd)

Figure	Title	Page
33	Oscillating Frequency - MHZ	93
34	Magnetron Trimming	95
35	Frequency Vs Power Output	96
36	Frequency Change From Sample Mean Megahertz	97
37	Microwave Power Output Watts	97
38	Magnetron Signal To Noise	98
39	Parallel Beam Region Within Fresnel Region	102
40	Transmission Efficiency Molecular Absorption And Rain	102
41	Ground System Costing	105
42	Square Slotted Array To Circular Rectenna	105
43	Polarization	108
44	Motor Mass Vs Motor Speed	111
45	Motor Efficiency Vs Maximum Design Speed	111
46	Drop In Motor-Controller Efficiency Vs Percent Loss In Motor Speed	112
47	Distributed Retrodirective Array Control	120
48	Central Control	120
49	Schematic Of Parametric Convergence Showing Major Options Considered	122
50	Generic Microwave Carbon Dioxide Observational Platform System	122
51	Transmission Efficiency For Optimum Field Distribution In A Microwave Beam	126
52	Makeup Of A Dual Linear Rectenna	130
53	Effect Of Altitude And Off Boresight Angle On Transmittal Microwave Beam For A Flat Phased Array	132

LIST OF FIGURES (Cont'd)

Figure	Title	Page
54	The Angular Relationship Of Antenna And Rectenna A Microwave-Powered Aircraft	136
55	Computed E-Plane Antenna Pattern For An 8 x 8 Slot Radiating Element In A Flat Array	141
56	Computed H-Plane Antenna Pattern For An 8 x 8 Slot Radiating Element In a Flat Array	142
57	Computed E-Plane Antenna Pattern For A 39 x 78 Meter Array	143
58	Computed H-Plane Antenna Pattern For A 39 x 78 Meter Array	144
59	System Considerations And Tradeoffs	147
60	Ranges Of Design Variables Examined During The CO-OPS	147
61	First System RDT&E Cost Vs Platform Cruise Altitude For A Platform With A Disk Rectenna And A Flat Slotted Array	149
62	Sample Plot Of The Effect Of Aspect Ratio On Power-To-Mass Ratio And Wing Loading For A Microwave Hale RPV	151
63	The Effect Of Aspect Ratio Variations On Power-To-Mass Ratio And Wing Loading For Several Wingspans For A Microwave Hale RPV	151
64	Parametric Plot Of Microwave Hale RPV Showing Constraint Lines	152
65A	Effect Of Altitude Variations On First System RDT&E Cost For A Flat Slotted Array And A Disk Rectenna	157
65B	Effect Of Altitude Variations On First System RDT&E Cost For A Flat Slotted Array And A Wing Rectenna	157
66A	Effect Of Altitude Variations On First System RDT&E Cost For A Solid State Array And A Disk Rectenna	157
66B	Effect Of Altitude Variations On First System RDT&E Cost For A Solid State Array And A Wing Rectenna	157

LIST OF FIGURES (Cont'd)

Figure	Title	Page
67A	Effect Of Altitude Variations On First System RDT&E Cost For An 11 Meter Dish Array And A Disk Rectenna	158
67B	Effect Of Altitude Variations On First System RDT&E Cost For An 11 Meter Dish Array And A Wing Rectenna	158
68A	Effect Of Altitude Variations On First System RDT&E Cost For A 4a.5 Meter Dish Array And A Disk Rectenna	158
68B	Effect Of Altitude Variations On First System RDT&E Cost For A 4.5 Meter Dish Array And A Wing Rectenna	158
69A	Effect Of Altitude Variations On First System RDT&E Cost For A Slotted Array On Pedestals And A Disk Rectenna	159
69B	Effect Of Altitude Variations On First System RDT&E Cost For A Slotted Array On Pedestals And A Wing Rectenna	159
70A	Effect Of Altitude Variations On First System RDT&E Cost For A Flat Slotted Array And A Disk Rectenna	159
70B	Effect Of Altitude Variations On First System RDT&E Cost For A Flat Slotted Array And A Wing Rectenna	159
71A	Effect Of Altitude Variations On First System RDT&E Cost For A Solid State Array And A Disk Rectenna	160
71B	Effect Of Altitude Variations On First System RDT&E Cost For A Solid State Array And A Wing Rectenna	160
72A	Effect Of Altitude Variations On First System RDT&E Cost For An 11 Meter Dish Array And A Disk Rectenna	160
72B	Effect Of Altitude Variations On First System RDT&E Cost For An 11 Meter Dish Array And A Wing Rectenna	160

LIST OF FIGURES (Cont'd)

Figure	Title	Page
73A	Effect Of Altitude Variations On First System RDT&E Cost For A 4.5 Meter Dish Array And A Disk Rectenna	161
73B	Effect Of Altitude Variations On First System RDT&E Cost For A 4.5 Meter Dish Array And A Wing Rectenna	161
74A	Effect Of Altitude Variations On First System RDT&E Cost For A Flat Slotted Array On Pedestals And A Disk Rectenna	161
74B	Effect Of Altitude Variations On First System RDT&E Cost For A Flat Slotted Array On Pedestals And A Wing Rectenna	161
75	Variation Of First System RDT&E Cost With Operational Altitude	175
76	CO-OPS Payload Subsystem Uncertainties	179

LIST OF TABLES

Table	Title	Page
1	Categories Of Atmospheric And Earth Observations	7
2	Category-To-ODR Correlations For CO-OPS Study	8
3	Site-To-ODR Correlations For CO-OPS Study	9
4	Microwave Power Transmitter Options	14
5	Antenna Options	15
6	Summary Of Instrument Complements	18
7	Further Desired Instrumentation	19
8	Viable Ground Power Subsystem Options First System Hardware Costs	19
9	Viable Platform Subsystem Options	20
10	Cost Of Subsystem Mobility	21
11	Potential Payload Complement For The Prototype Verification Test Site	22
12	Viable Combinations Of Ground And Platform Subsystems	25
13	Categories Of Atmospheric & Earth Observations	37
14	Category-To-Observational Data Requirement Correlations For This Study	38
15	Site-To-Observational Data Requirement Correlations For This Study	40
16	Allocation Of Instruments For CO-OPS ODR & Mission Categories	46
17	Summary Of Instrument Complements	48
18	Further Desired Instrumentation	49
19	Summary Of Key Parameters	50
20	Viable Platform Subsystem Options	69
21	Alternative Power Trains	70
22	Antenna Approaches	82
23	Comparison Of Transmitter Approaches	87
24	Power Transfer	100
25	Government Use Frequency Allocation	103
26	EMI Required Performance Improvements	104
27	Rectenna Considerations	106
28	Diode Selection	109
29	Gearbox Parameters	110
30	Data System Approaches-Platform/Ground System	114
31	Steering And Focus Control Requirements	116
32	Power Control	117
33	Steering And Focus Control	118
34	Practical Reasons For Restricting The Transmission Efficiency Factor	127
35	Antenna Array Options	127
36	Pattern Efficiency Dependence	128
37	Packing Factor For A Rectangular Grid	128
38	Optimum CO-OP Systems For Major Subsystem Alternatives	154
39	Three Recommended CO-OP Systems	156
40	Maintenance Cost Summary	166
41	CO-OPS System Study	166

LIST OF TABLES (Cont'd)

Number	Title	Page
42	Slotted Array On Pedestal	167
43	Viable Groundpower Subsystem Options	170
44	Cost Of Subsystem Mobility	171
45	Viable Platform Subsystem Options	172
46	Viable Combinations Of Ground And Platform Subsystems	173
47	Summary of Instrument Complements	176
48	Further Desired Instrumentation	177
49	Potential Payload Complement For The Prototype Verification Test Site	178

EXECUTIVE SUMMARY

Introduction

The Carbon Dioxide Observational Platform System (CO-OPS) feasibility system-study investigated concepts for a long-duration, near-space geo-stationary monitoring platform with capability of supporting a variety of potential applications. The Department of Energy (DOE) and NASA/Marshall Space Flight Center (NASA/MSFC) initiated the study to determine the feasibility of a CO-OPS capability to satisfy near-term needs of the DOE Carbon Dioxide Research Program and generic needs for Regional (mesoscale) observations over long periods of time.

The need for high-altitude observations has long been recognized, and both systems and technology studies done within the U.S. Government (DOE, DoD, NOAA, NASA, and Department of Interior) and the Canadian Government have shown the need for near-space geostationary platforms and postulated several alternatives. The concept of high-altitude powered platforms for application to the DOE CO2 Research Program was introduced in the NASA CR3923 report, "System Study of the Utilization of Space for Carbon Dioxide Research." The near-term feasibility of microwave-powered high-altitude platforms was also indicated by the NASA TM84508 report, "The Feasibility of a High-Altitude Aircraft Platform with Consideration of Technological and Societal Constraints." This concept typically would fly at altitudes of 18 to 24 kilometers (60,000 to 80,000 feet) at relatively modest maximum cruise speeds of 60 m/s (117 Knots) while being continuously supplied with power for its electric motor by a microwave beam from the ground. The payload capacity of 227 to 680 kilograms would be adequate for multi-sensor payloads provided by potential users.

To satisfy this need, a variety of observational systems have been used to gather such data. Among the most widely used have been:

- Satellites, in both geosynchronous and low earth orbits
- Rocket Sondes
- High-Altitude Observational Piloted Aircraft
- Balloons

These platforms are shown schematically in Figure 1. All of these systems were successful, to some extent, in obtaining atmospheric and/or biospheric data, although none accomplished the in-situ, long-duration observations desired.

The introduction of the CO-OPs in addition to enhanced observational capabilities satisfies the observational requirements in a most cost-effective manner as shown by comparing the various systems' costs.

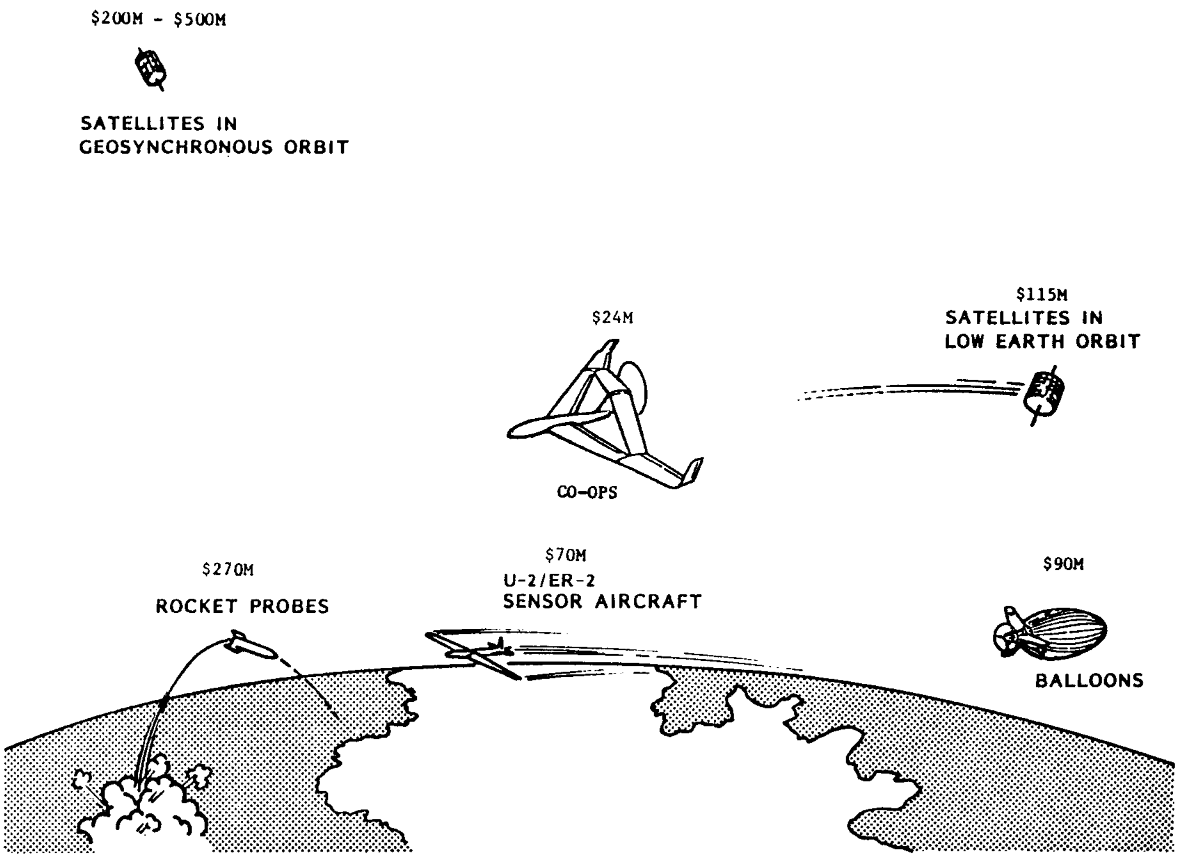


Figure 1. Observational Platforms

ORIGINAL PAGE IS
OF POOR QUALITY

System costs are rough-order-of-magnitude (ROM) and are for perspective only. The satellite cost estimates are from the report, "System Study of the Utilization of Space for Carbon Dioxide Research," NASA CR 3923 and from "Aerospace America," April 1986. The rocket probe costs are from a Sandia Labs estimate and reflect the need to launch one every hour, around the clock, to satisfy hourly ODR observations. The U-2 costs are estimates from Lockheed's ADP "Skunk Works," and the balloon costs are from a Lockheed Missiles and Space Co. "Hi-Spot" report. As nearly as possible, all costs were based on the Research, development, test, and evaluation (RDT&E) and acquisition costs for one vehicle plus one year's operational costs.

Recognizing the need for Regional (mesoscale) observations over long periods of time in order that the scientific community be accurately informed to recommend timely action, the DOE and NASA/Marshall Space Flight Center (NASA/MSFC) initiated the Carbon Dioxide Observational Platform System feasibility study.

This 11-month Pre-Phase A study, which began in June 1985, was to determine the feasibility of a CO-OP System to satisfy the near-term observational needs of the DOE CO Research Program. Phase A: Concept Definition, Phase B: Engineering Development, and Phase CD: Prototype, Test and Operations, are to follow with first flight of a prototype system in the 1989-1990 time frame.

Both system and technology studies done within industry, the U.S. Government and the Canadian Government have shown the need for near-space geo-stationary platforms and postulated several alternatives. The purpose of this system feasibility study has been to assess past work, analyze a specific current need, and make recommendations or viable alternatives.

Study Objectives and Guidelines

The objective of this work has been to perform a feasibility study of a CO-OP System to satisfy the near-term observational needs of the DOE CO Research Program. To be feasible all subsystems had to be essentially off-the-shelf-hardware that could be modified and integrated into a cost-effective operational prototype system by 1990. The microwave subsystems investigation included antenna power source tradeoffs of magnetron vs klystrons or solid-state power supplies. Flat antenna versus dishes, 2.45GHz vs 5.8GHz operating frequencies, focused versus non-focused beams, and irated subsystem efficiencies were among the major microwave considerations. Platform tradeoffs were primarily in the area of platform geometry (wing shape), drag, and power required. The ground power subsystem costs proved to be very sensitive to power required at the aircraft rectenna and the subsystems configurations of the ground power antenna system itself. The main thrust of the study therefore was to establish descriptions and equations of all system driver combine them in a computer program according to their sensitivities to the overall CO-OP objective function (cost/operational capability) and, by successive iterations, arrive at the most feasible CO-OPS system. To do this, it has been necessary to examine the system as a whole, identify design parameters that are system drivers, and create system cost trends versus observational capabilities. The depth of detail in this study has been only that required to assure a look at all alternatives with a well-balanced examination of those appearing most promising for a near-term (1990) initial operational capability (IOC).

Guidelines provided for this study were the Observational Data Requirements (ODRs) established in 1983-84 as a result of a study performed for NASA/MSFC entitled "The Utilization of Space for Carbon Dioxide Research." One of the near-term options identified by this study was a near-space geo-stationary platform carrying the recommended Carbon Dioxide Research Satellite (CORS) payload. Other guidelines were an operational altitude of from 5 to 40 kilometers (16,405 to 131,240 feet), a payload mass of from 227 to 680 kilograms (500 to 1500 pounds-force), and continuous measurements for a time period of 60 to 90 days. A cost goal was established for a first system RDT&E cost of around $30 million in 1984 dollars.

Study Overview

The CO-OP System feasibility study just performed started with a very large number of combinations of performance parameters, possible subsystems and systems, all with their associated impacts on system performance, cost, and schedules. The distilling of these options to several viable systems which is the essence of this Pre-Phase A study.

Figure 2 shows the parametric convergence used during this system study. Platform subsystem options were in the tens of thousands by the time all viable combinations of basic geometric parameters were considered. Ground antenna subsystem options, while not as numerous as platform subsystem options, had many variations in component hardware. Some subsystem options could be ruled out for detailed consideration in comparison with other subsystems. Others were only shown to be less viable after consideration in full systems. The parametric system sizing methodology used during this study was characterized by its flexibility in modeling diverse options.

To establish a perspective, a typical CO-OPS platform might have a wingspan of about 30 meters (98 feet) and weigh 900 kilograms (1984 pounds) with a power requirement to the ground transmitter of around 2 million watts. The area occupied by the ground transmitters would be approximately 60 meters (196 feet) in diameter.

Requirements Definition

The first task initiated during this study was the definition of mission, payload, technology, and cost requirements of subsystems and of the CO-OP System. Results were expressed as constraints, and tests were applied at various points in a comprehensive parametric system sizing methodology. In parallel with this work was an identification of existing representative payloads that could accomplish the ODR objectives while analyzing the design impact of the payloads on the platform system. The

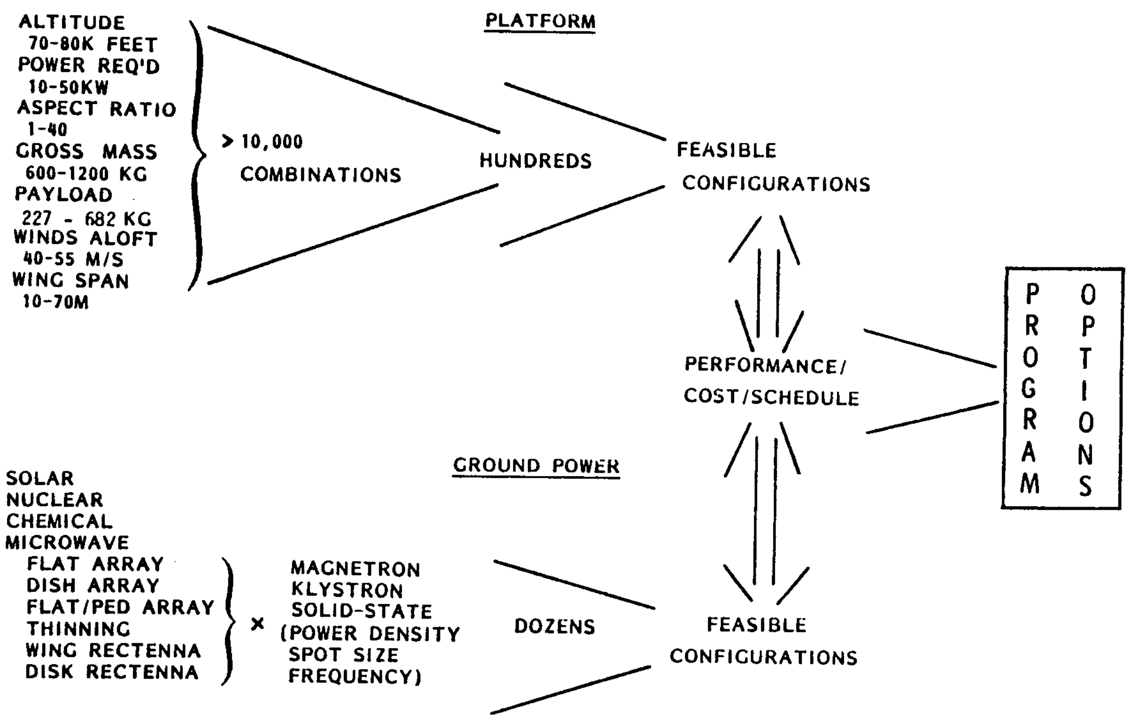


Figure 2. Parametric Convergence

payloads will be discussed further in the next section. The primary mission will be discussed first. Next will be other missions and applications. The final paragraphs in this section will discuss system and subsystem requirements as applied to potential mission payload complements.

Primary Mission and Location. The purpose of CO-OPS is to verify system capability to operate in the upper atmosphere continuously for months at a time over a long period (up to 10 years). The system will be capable of operating at a variety of sites, with similar environmental conditions. Five site categories were examined during this study. The primary mission will take place at the prototype verification test site. A candidate location is Site 1, NASA/MSFC.

The potential payload complement will be a variety of climatological sensors that were originally chosen specifically for a CORS payload. All payloads have been considered user-supplied for costing purposes.

Other Applications and Utilizations. The CO-OP System is capable of fulfilling a variety of additional missions with little or no modification to either the platform or the ground subsystems. Particularly interesting missions are discussed in the next four paragraphs.

The first alternate mission is as a communications relay, which has applications to virtually every country in the world and to businesses that need low-cost regional relay platforms. Flying at an altitude of 20 to 22 kilometers (65,000 to 72,000 feet), a CO-OP System platform could retransmit radio, television, microwave, or laser signals between points on the ground up to 1300 kilometers (700 nautical miles) away. The Canadian Government has studied applications of microwave- powered high-altitude relays for this mission in the Stationary High-Altitude Relay Platform (SHARP) program. SHARP design criteria can be applied to the CO-OP System to determine the feasibility of CO-OPS for this mission.

A second interesting mission is weather observation. The CO-OP System could be instrumented for thunderstorm phenomenological observation and stationed either above a line of thunderstorms or off to one side. This mission is being studied at NASA/MSFC (Ref. 9) and could be demonstrated with a CO-OP System at the prototype verification test site with additional instrumentation weighing 22.7 kilograms (50 pounds-force) and a slight wattage increase to the CO-OPS prototype payload complement.

A third potential ancillary mission is off-shore monitoring. The CO-OP System could be placed close to shorelines to observe shipping traffic within U.S. Territorial Waters and within the 200 nautical miles (371 kilograms) fishing limit. With the platform cruising at an altitude of 20 kilometers (65,600 feet) the radio horizon would be 556 kilometers (300 nautical miles) away. This mission has been studied by the U.S. Coast Guard.

A fourth potential mission is forestry observation. The U.S. Forestry Service has an ongoing need to monitor the health of forested lands. One or more stationary CO-OPS platforms could monitor forests in the West and pass data between ground stations. Forests could be observed for general health as well as for fire prevention. Onboard sensors would also be capable of detecting the hottest spots in forest fires and the CO-OP System might provide targeting information to aerial bombers.

Summary of Observational Data Requirements for Each Site. The DOE has identified six categories of desired observations as part of its mandate to monitor CO in the atmosphere. These categories are presented in Table 1.

TABLE 1. CATEGORIES OF ATMOSPHERIC AND EARTH OBSERVATIONS

CATEGORY	TOPIC
A	ATMOSPHERIC PROFILES
B	ATMOSPHERIC SPECIES
C	CLOUDS
D	SEA/OCEAN
E	SNOW/ICE
F	SURFACE CONDITIONS

Note that Category A, B, C, and F measurements would apply at any observation site, while category D would apply only for an ocean site. Category E measurement would be of interest where snow and ice were the dominant surface cover.

The Observational Data Requirements (ODRs) are reproduced in Appendix A of this report. ODRs are listed in alphabetical order, have numbers for reference purposes and are correlated in Table 2 with the above categories.

Site-to-ODR correlations are presented in Table 3, which also presents the types of instrumentation required to make the observations indicated in Table 1. Thus, to identify the required payload complement for each observation site, compare the list of required instrumentation to the available instruments.

Observation Sites. DOE has identified five possible CO-OPS observation sites. These are presented below in order of descending emphasis in this study.

- o Site 1, the prototype verification test site which may be NASA/MFSC
- o Site 2, either Vandenberg Air Force Base or Edwards Air Force Base
- o Site 3, along the east coast in the New Jersey area
- o Site 4, sites particularly suitable to measurement of carbon dioxide buildup such as the west Antarctic, the intertropical zone (Panama), and the east coast north of 60° north latitude
- o Site 5, any target of opportunity

TABLE 2. CATEGORY-TO-ODR CORRELATIONS FOR CO-OPS STUDY

CATEGORY/TOPIC	ODR	OBSERVABLE
A: ATMOSPHERIC PROFILES	21	VERTICAL TEMPERATURE PROFILE
	22	VERTICAL WATER VAPOR PROFILE
	23	WIND FIELD
B: ATMOSPHERIC SPECIES	1	AEROSOL CONCENTRATION
	2	ATMOSPHERIC CONCENTRATIONS, CO_2
	3	ATMOSPHERIC CONCENTRATIONS, TRACE GASES
C: CLOUDS	5	CLOUDS, CIRRUS
	6	CLOUDS, FRACTIONAL COVERAGE
	7	CLOUDS, VERTICAL STRUCTURE
	10	RADIANCE AT TOP OF THE ATMOSPHERE
D: SEA AND OCEAN	11	SEA CURRENTS
	12	SEA ICE
	13	SEA LEVEL
	14	SEA SURFACE TEMPERATURE
	15	SEA SURFACE WINDS
E: SNOW AND ICE	8	LAND ICE
	16	SNOW COVER
F: SURFACE CONDITIONS	4	BIOSPHERE, VEGETATION INDEX
	9	PRECIPITATION
	17	SURFACE ALBEDO
	18	SURFACE ATMOSPHERE PRESSURE
	19	SURFACE MOISTURE, SOIL
	20	SURFACE TEMPERATURE, SOIL

TABLE 3. SITE-TO-ODR CORRELATIONS FOR CO-OPS STUDY

DESIRED SITE COVERAGE	CATEGORY	TOPIC	ODR	INSTRUMENTATION REQUIRED
1,5 2,3 4	A	ATMOSPHERIC PROFILES	21	TEMPERATURE SOUNDER
			22	HUMIDITY SOUNDER
			23	RADAR SCATTEROMETER
	B	ATMOSPHERIC SPECIES	1	ACTIVE OR PASSIVE SPECTROMETERS
			2	IN-SITU PLATFORM SENSORS. A,B
	C	CLOUDS	5	TEMPERATURE SOUNDER/ RADIOMETER
			6	IMAGING RADIOMETER
			7	PARALLAX IMAGING SOUNDERS/RADIOMETERS
			10	TOTAL RADIATION MONITORS
	D	SEA AND OCEAN	11	ALTIMETER AND/OR OCEAN CHLOROPHYLL IMAGER
			12	HUMIDITY SOUNDER/ VISIBLE, NIR,IR IMAGER
			13	ALTIMETER
			14	TEMPERATURE SOUNDER, RADIOMETER
			15	ALTIMETER, RADAR SCATTEROMETER
	E	SNOW AND ICE	8	ALTIMETER
			16	HUMIDITY SOUNDER (MICROWAVE)
	F	SURFACE CONDITIONS	4	NIR RADIOMETER, SELECTED VEGETATION BANDS
			9	HUMIDITY SOUNDER
			17	VISIBLE RADIOMETER
			18	GROUND BASED SENSOR (?)
			19	MICROWAVE SOUNDER
			20	TEMPERATURE SOUNDER/ RADIOMETER

Payload Subsystem. The level 1 payloads (those that are available off-the-shelf within the next five years), were used for sizing and design considerations for the platform.

The payload subsystem task provided the needed inputs to accomplish the primary study objective of determining whether long-term earth observation missions are technically feasible from a near-space geo-stationary monitoring platform. Interface requirements that impacted the ability of a platform configured to accommodate a typical applications payload had to be assessed first.

The key issues involved in the CO-OP System are those that affect the ability of the system to achieve mission goals. The top-level mission goals are:

- Continuous in-situ measurements from one to three months at altitude

- Capability of making a variety of earth, ocean and atmospheric measurements

- Ensuring that the system, and its subsystems, are
  - Portable
  - Retrievable
  - Redeployable
  - Capable of remote operation

Many lower level mission goals stem from these. The study determined and addressed the issues that affected system feasibility to achieve these top-level goals.

The ODRs provided by the scientific community for the first phase of the NASA study mentioned earlier were used to select typical instrument complements. These complements then allowed determination of required platform interfaces for a wide assortment of payloads.

Platform Subsystem. Before considering platform configurations, it is necessary to address the power source options for the platform. This power source could be supplied either internally or externally.

Internal power source options include the internal combustion engine (reciprocating, turbojet, turbofan, and cryogenic), radioisotope, fuel cell, and electric battery. External power source options include solar and microwave.

For long-endurance near-space applications this list of power options can be narrowed to just radioisotope, solar, and microwave generators. The radioisotope thermoelectric generator option was eliminated by safety and environmental considerations. While solar power offers a potentially viable solution for daytime operations, the current weight of an energy source for nighttime operations eliminates solar power as a viable near-term solution. Hence, a ground-based microwave power subsystem was selected as the focus for the power source of CO-OPS.

A wide variety of platform subsystem configurations was examined during this feasibility study. These included both heavier-than-air and lighter-than-air alternatives including these generic fixed-wing configurations:

- A conventional monoplane with a disk rectenna beneath the fuselage or a wing-mounted rectenna

- A joined wing with a disk or wing-mounted rectenna.

The emphasis of this study quickly focused on heavier-than-air platforms following the initial assessments of lighter-than-air and other concepts which were dropped from further considerations the reasons summarized below.

Several studies have been done in recent years on applications of airships to a wide variety of civilian and military missions. This work was reviewed during this study, and some conclusions were reached about the applicability of airships to CO-OPS missions. A semi-rigid, high-altitude, long-endurance airship for a military mission with payload, time-on-station, and airspeed comparable to the primary CO-OPS mission was postulated in the "Design Studies for a Ground Microwave Power Transmission System for Use with a High-Altitude Powered Platform," NASA CR-168344. The airship was around 180 meters (591 feet) in length, had a non-buoyant takeoff gross mass of around 12,000 kilograms (26,400 pounds-force) and required up to 155 kilowatts (208 horsepower) of thrust power. Its volume was around 42,000 cubic meters (1.5 million cubic feet), making it larger than the Goodyear airships by a considerable margin. In addition, all sources pointed out some generic problems with high-altitude (60,000 to 80,000 feet) airships:

- Large diurnal effect. Internal gases expand and contract daily requiring careful center-of-buoyancy management.

- Significant launch problems require further development (e.g., in late 1975 during the High-Altitude Superpressured Powered Aerostat (HASPA) program, the three launch attempts all ended in destruction of the vehicles during the vertical launch mode.)

- Airships tend to get much larger with increasing speed .

- Required thrust power increases with both size and speed.

For these reasons, airships were not investigated further for CO-OP System missions within the timeframe required by study guidelines.

The platform subsystem was modeled in each of three ways during this study. The three are shown in Figure 3. The first represents a clean aerodynamic shape carrying a circular rectenna that is held to 65 percent of wing area for comparison with the second generic configuration discussed

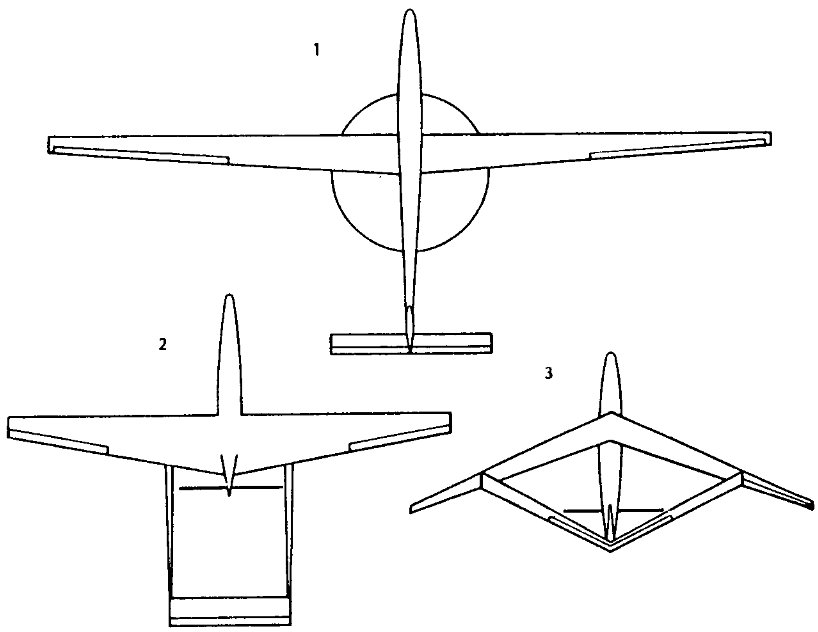


Figure 3. Generic Configurations

below. This generic configuration was one of several examined by the Canadian Department of Communications in its ongoing Stationary High-Altitude Research Platform (SHARP) program.

GENERIC CONFIGURATIONS

The second generic configuration examined is a conventional aircraft with a rectenna mounted on the wing undersurface. Configuration parameters modeled represent both ends of a spectrum of possible platforms. In one case, the platform is made as aerodynamically clean as possible at the expense of microwave reception to minimize subsystem cost. At the other, platform aerodynamic cleanliness is compromised to see if total first system RDT&E cost can be lowered. Propellers are placed aft to keep vortices from interfering with the lift distribution on the wing and to avoid obstructing payload viewing windows. The rectenna conforms to the undersurface of a tapered wing and can be no larger than about 65 percent of wing reference area. This 65 percent, referred to as the rectenna packing factor, is one criterion applied to parametric analyses to be discussed in Section 8.5. The 65 percent upper limit on relative rectenna area allows for non-flat portions of the wing undersurface occupied by leading and trailing edges, wing fillets, and control surfaces. The optimum geometric surface to attach the rectenna to would be a flat plane.

The third generic configuration is a joined wing developed by Dr. Julian Wolkovitch of ACA Industries. It has weight-saving and aerodynamic properties that may make it particularly applicable to the CO-OP System mission. This configuration is between the two extremes just discussed in that a large amount of undersurface area is available for rectenna even though the platform is aerodynamically quite clean. This configuration also lends itself well to a disk-shaped rectenna.

A configuration with a high aspect ratio, slender wing has the least drag and power required but necessitates a large diameter power circle to focus on the rectenna on the wings underside. Most of the focused power (90 to 95 percent) is wasted. A very low aspect ratio wing (e.g., the shape of a circle) matches the power circle geometry very well but has extremely high drag and thus high power requirements. Therefore, these very high and very low aspect ratio platforms bound the system configuration problems with the optimum, lowest cost system somewhere in between these.

Ground Power Subsystem. This study considered six ground power subsystems consisting of a flat array or dish antennae array with its power transmitter of either a magnetron, klystron, or solid-state supply. These were:

- Flat slotted phased array using magnetron tubes as power sources
- Flat slotted phased array using klystron tubes as power sources, mounted on pedestals

- A phased array made up of dishes on separate pedestals with klystron tubes
- A phased array made up of dishes with Cassegrainian power feeds on separate pedestals, with klystron tubes
- A flat solid state phased array
- A flat phased array using magnetron tubes with panels mounted on pedestals

Each was modeled in moderate detail in a parametric system sizing methodology. When combined with the two rectenna alternatives, disk-mounted or wing-mounted, a total of 10 options were examined. Table 4 summarizes power transmitter options, and Table 5 summarizes antenna options. Not all power transmitters were combined with all ground antennae options. Only those combinations from Tables 4 and 5 that were technically and/or cost effective were used to make up the ground power subsystems shown in Table 8. The solid-state power transmitters, while technically feasible, were considered outside the cost goal and schedule guidelines of this study.

TABLE 4. MICROWAVE POWER TRANSMITTER OPTIONS

CANDIDATE	TRANSMITTER COST	POWER OUTPUT	ADVANTAGES	DISADVANTAGES
Magnetrons	$1.50/w-3.90/w	500w-1kW	Up to 5kW	Injection Locking
		S-Band Only	Up to 1kW Air Cooled	S-Band Only 5kW Liquid Cooling/ HV Supply Highest Spurious Noise
Klystron	$3.00/w-5.30/w	20kW-300kW	Simple Output Control	Liquid Cooling Longest Replacement
			Lowest Spurious Radiation	Time HV Supply
solid-state	$12.00/w	5w-20w S-Band Only	Longest Life Lowest Maintenance Radiant or Air Cooling Low Voltages	Highest Cost/Watt CB and Devices in Development

TABLE 5. ANTENNA OPTIONS

CANDIDATE	COST	ADVANTAGES	DISADVANTAGES
Slotted Array with magnetrons	\$700-\$900/sq.m.	Lowest Cost Lowest Maintenance All Electronic Steering High Efficiency	Most Difficult Environmental Protection Low Scan Angles Preferable
Slotted Array with Two-Axis pedestal	\$1.0K-\$1.3K/sq.m.	High Angle Coverage Highest Efficiency No Blockage Trailer Mount Possible	Mechanical Mount Wind Loading
Cassegrainian Reflector with Feed Scan or SubReflector Scan	\$1.7K-\$1.9K/sq.m.	Low Inertia Mechanical Scan Trailer Mount Possible	Scan Coverage Limited to About 4 Beamwidths Highest Blockage Loss Lowest Efficiency

Subsystem Interactions

Payload Interaction with Platform and Ground Antenna. Payload factors affecting system ability to take continuous in-situ measurements for long durations are payload mass, drag producing payload attachment features such as viewing ports or fairings, and odd viewing angles for calibration. Features that create drag result from the need for instrument ports in the platform skin or bulges to fair the lumps and corners. Viewing ports are required to ensure that the platform provides those interfaces required to achieve the second mission goal of multiple observations. Required viewing ports will depend on the particular observation. NADIR viewing instruments and scanners looking through NADIR will require a clear view of earth. Limb-viewing instruments will require a clear view of the earth's limb. Some limb scanners must observe the sun as it rises and sets and, hence, may determine platform flight path during part of each day's mission. Solar-viewing instruments must be able to continuously track the sun during the day. Most instruments will need frequent calibration by viewing the sun and/or deep space. Platform structure must be excluded from the viewing envelope in all cases. To summarize, viewing requirements will necessitate:

- Placement of payload instruments on the platform in accordance with the viewing requirements of each payload instrument
- Careful coordination between the payload observation timeline and the operational timeline flight plan of the platform.

Payload viewing requirements may dictate modifications to the instruments for shielding sensors from the microwave energy. Such modifications could be costly and should be kept to a minimum.

To successfully make the required ODR observations, payload contamination (i.e., water, ice, dust, low temperatures) must be rigorously controlled. The necessity for contamination control will place requirements on the design and operation of the platform. Protection of the payload will be required during all phases of the mission including preflight, climb to altitude, daily operations, descent, and recovery.

Instruments with components at cryogenic temperatures will require special attention to preclude icing. Certain infrared instruments require cooled detectors to achieve low-noise measurements. Passive cooling using a radiative cooler is typical, and the cooler is designed to couple the detector to cold deep space. In addition, warm windows would be required over the detector and over the radiative cooler inner stage to prevent contamination buildup. At a minimum, the detector window will require refocus of the payload optics system. The window may require further redesign of the instrument and may adversely affect radiometric performance. The radiative cooler inner stage window, if needed, may adversely affect the cooler's ability to radiatively cool the detectors. Hence, other means may be necessary. Alternatives might be passive stored cryogen or an active refrigeration system.

Since the platform is bathed in microwave radiation, the instruments must operate in this environment. This may require shielding of instruments and cables, microwave barriers and/or isolation shields as discussed in more detail in Section 4.0, Payload Subsystem.

Ground Antenna Interaction with Platform. One of the major system cost drivers is the interaction of the diameter of the focused microwave power beam, or spot, relative to rectenna and platform geometries. At a nominal altitude of 20 kilometers (65,600 feet), the microwave power spot varies with the geometry of the platform from about 10 to 40 meters (33 to 131 feet) in diameter. Power density, measured in watts per square meter, is the greatest at the center of this spot and decreases roughly logarithmically toward the edges. Useful power is usually considered to exist between the center and a radius established at the points where power has decreased to one-half the value at the center of the spot. This smaller circle, known as the half-power circle, ideally should correspond to the diameter of the platform's rectenna. If the rectenna is a disk, then its diameter is limited to this value. There is a corresponding ground antenna diameter to produce the required spot size for every ground power option.

There are a wide variety of platform subsystem shapes to carry the rectenna. These shapes may vary from a circular wing of just more than aspect ratio 1 and slightly larger than the half-power circle in diameter to a very efficient sailplane wing of very high aspect ratio. The highly efficient aerodynamic shape will require less power than a less efficient shape but will intercept less of a circular spot. Because less is intercepted by a highly efficient sailplane type wing, more power must be beamed up and more must be generated on the ground requiring a larger array. The tradeoff to be performed, then, is between highly efficient subsystems aloft and on the ground and less efficient subsystems optimized to work together to minimize total system cost. Platform subsystem configuration and ground subsystem options change the details of this trade, but not the basic logic.

Viable Systems and I.O.C. Options

After extensive parametric analyses using the system sizing methodology described in the main body of this report, several viable CO-OP Systems were identified. These can be summarized by subsystem.

Payload Subsystem

Site 1 and 5 Initial Payload and Site 2.3.4 Additional Payload. Based on ODR/site/payload capability tradeoffs, the instrument complement listed in Table 6 would permit satisfaction of almost every ODR. Assuming a hierarchical approach to acquisition of the instruments, the complement for initial Site #1 observations would consist of some subset of the listed instruments. Planning by users active in these research fields is required to select the best instruments. This complement would also satisfy the ODRs for Site #5. The addition of two instruments to this complement, the CZCS or OCI ocean color imager and the ALT altimeter, would permit satisfaction of the ODRs for the additional sites discussed here.

Further Desired Instrumentation. Table 7 lists some additional instruments that would be needed to satisfy the remaining ODRs.

In addition to these platform subsystems that sized for moderately high-altitude operation, a platform was sized for operation at an altitude of 37 kilometers (121,000 feet). This platform would have a wingspan of 110 meters (361 feet) with a total system RDT&E cost of between $200 million and $300 million in 1984 dollars.

Ground Subsystem

Platforms were sized with specific ground antenna and power transmitter options, as presented in Table 8.

Platform Subsystem

Several platform subsystems appear viable for use in a CO-OP System. Presented in Table 9 are 10 platforms with indications of mass, size, flux density, cost, and development readiness. Cruise airspeed used is 50 Meters per second (97 knots) at altitudes from 19 to 21 kilometers (62,000 to 70,000 feet) and payload mass is 270 kilograms (595 pounds-force). The A, B, C, D, and E refer to the ground power subsystems listed in Table 8.

TABLE 6. SUMMARY OF INSTRUMENT COMPLEMENTS

INSTRUMENT	INSTRUMENT CAPABILITY
HIRS-2 (HIGH RESOLUTION INFRARED SOUNDER 2)	TEMPERATURE SOUNDING AND WATER VAPOR PROFILE
SAGE-2 (STRATOSPHERIC AEROSOL AND GAS EXPERIMENT-2)	VISIBLE, NIR, IR IMAGING RADIOMETER
SAGE-2 (STRATOSPHERIC AEROSOL AND GAS EXPERIMENT-2)	AEROSOL AND GAS MEASUREMENT AT LIMB
SMMR (SCANNING MULTI-CHANNEL MICROWAVE RADIOMETER)	HUMIDITY SOUNDING ICE AND WIND
SBUV/TOMS (SOLAR BACKSCATTER ULTRAVIOLET RADIOMETER-TOTAL OZONE MAPPING SPECTROMETER)	OZONE PROFILE UV SOLAR IRRADIANCE
ERBE (EARTH RADIATION BUDGET EXPERIMENT)	SOLAR OUTPUT EARTH RADIATION IN THREE BANDS: -TOTAL (0.2 TO 50 MICROMETERS) -SHORT WAVE (0.2 TO 5 MICROMETERS -LONG WAVE (5 TO 50 MICROMETERS)
SCAT (SCATTEROMETER)	WIND FIELD, BOTH SPEED AND DIRECTION
ASAS (ADVANCED SOLID-STATE ARRAY SPECTRORADIOMETER)	SILICON CHARGE-COUPLED DEVICE PUSHBROOM IMAGING SPECTRORADIOMETER
THIR (TEMPERATURE, HUMIDITY INFRARED RADIOMETER)	IMAGING TEMPERATURE AND HUMIDITY RADIOMETER CLOUDS, WATER VAPOR
<u>ADDITIONS FOR SITES #2,3 AND 4</u>	
ALT (ALTIMETER)	RADAR ALTIMETER
CZCS/OCI (COASTAL ZONE COLOR SCANNER/OCEAN COLOR IMAGER)	OCEAN SURFACE CHARACTERISTICS SURFACE TEMPERATURE

TABLE 7. FURTHER DESIRED INSTRUMENTATION

INSTRUMENT	ADDED CAPABILITY
ATMOS. LASER HETERODYNE SPECTROMETER OR LIMB SCANNING SPECTROMETER	CARBON DIOXIDE AND TRACE GASES (ODR 2,3)
PARALLAX SENSOR	CLOUD VERTICAL STRUCTURE (ODR 7)
IN-SITU MONITORS ON PLATFORM	TEMPERATURE PRESSURE WIND VELOCITY GAS AND AEROSOL SAMPLING PARTICLE CONCENTRATIONS
GROUND-BASED MONITORS	SOLAR FLUX MONITOR PLATFORM ALTITUDE, ORIENTATION, DIRECTION OF FLIGHT, SPEED, AIR PRESSURE

TABLE 8. VIABLE GROUND POWER SUBSYSTEM OPTIONS FIRST SYSTEM HARDWARE COSTS

SUBSYSTEM	INPUT POWER MW	DIA OR SIDE-M	MASS Kg	COST (1984 $M)	DEVELOPMENT READINESS
A. SLOTTED ARRAY ON PEDESTALS - WITH MAGNETRONS	1.15	72 DIA	50,300	15.34	EXC - GOOD
B. SLOTTED ARRAY FLAT - WITH MAGNETRONS	2.49	55 x 55	93,800	12.46	EXC - GOOD
C. 4.5M DISH WITH MAGNETRONS	1.28	93 DIA	93,500	22.95	EXC - GOOD
D. 11M DISH WITH KLYSTRONS	1.29	96 DIA	114,700	27.5	GOOD
E. SLOTTED ARRAY WITH SOLID-STATE	1.35	85 X 85	31,100	33.51	FAIR

TABLE 9. VIABLE PLATFORM SUBSYSTEM OPTIONS

RECTENNA	GROSS MASS	WING-SPAN	ASPECT RATIO	FLUX DENSITY REQUIRED	COST (1984$M)	DEVELOPMENT READINESS
WING WITH D	698KG	34M	14	510W/SQM	7.29	
WING WITH C	683KG	36M	16	490W/SQM	7.30	
DISK WITH D	755KG	40M	19	494W/SQM	7.94	
WING WITH A	785KG	40M	14	424W/SQM	8.16	SEE NOTE
DISK WITH B	778KG	44M	21	405W/SQM	8.32	
WING WITH E	807KG	40M	13	406W/SQM	8.33	
WING WITH B	821KG	42M	14	405W/SQM	8.54	
DISK WITH C	842KG	48M	21	411W/SQM	8.98	
DISK WITH E	858KG	50M	22	401W/SQM	9.23	
DISK WITH A	872KG	50M	22	419W/SQM	9.32	

NOTE: All platforms utilize state-of-the-art technology and manufacturing, therefore the development readiness of all ten configurations is considered excellent.

Mobility Options

If subsystem mobility is considered a mission requirement, cost of the ground subsystem will increase. Table 10 presents the changes in costs of both a Reflector array and a slotted array if mobility is considered.

Table 10 presents time and costs to move each type of ground subsystem once. It has been assumed that transportation costs to another site would be the same whether the subsystem is fixed or mobile. As an example of transportation cost level, an array made up of 100 11 meter dishes on pedestals could be loaded aboard a USAF/Lockheed C-141 transport and flown to McMurdo Sound in the Antarctic for around $25 million. As the chart points out, slotted arrays may be designed for mobility from the outset for a modest increase in subsystem cost; therefore, if mobility is a consideration, slotted arrays may be the more suitable alternative.

Altitude Options

Various altitude options were examined during the course of this study, from 6 to 40 kilograms (19,680 to 131,200 feet) and with payload masses ranging from 227 kilograms (500 pounds force) to 680 kilograms (1500 pounds force). All of these systems are capable of performing missions carrying

TABLE 10. COST OF SUBSYSTEM MOBILITY

ANTENNA TYPE	ITEM	FIXED SUBSYSTEM	MOBILE SUBSYSTEM	MOBILITY +COST DELTA
SLOTTED ARRAY 65MX65M	DESIGN/PRODUCTION/ASSEMBLY	$12M	$13.0M	
	DISASSEMBLY	1M	0.5M	
	TOTAL	$13M	$13.5M	$0.5M
	DISASSEMBLY TIME	1-2 MOS.	1-1.5 MOS.	
	REASSEMBLY TIME	2-3 MOS.	2-3.0 MOS.	
REFLECTORS 11M DIAMETER	DESIGN/PRODUCTION/ASSEMBLY	$17M	$48M	
	DISASSEMBLY	3M	1M	
	TOTAL	$20M	$49M	$29.0M
	DISASSEMBLY TIME	2-3 MOS.	1/2-1.0 MOS.	
	REASSEMBLY TIME	2-3 MOS.	1-2 MOS.	

the smaller payload. Above 24 kilograms (78,720 feet), system cost begins to increase markedly, as shown by Figure 4.

Study Recommendations

Summary of Payload Subsystem Study Results

The mass, power requirements and performance characteristics of an atmospheric observation payload were determined early in the CO-OP System Pre-Phase A study. Key interface parameters of the potential payload complement for the prototype verification test site are summarized in Table 11. A total of 10 instruments will be required to meet ODR sensing requirements over the site. The heaviest package will probably weigh 276 kilograms (607 pounds force) and might require a total of 369 watts of power during their duty cycles. This would be a payload consisting of SCAT-A and the SMMR.

TABLE 11. POTENTIAL PAYLOAD COMPLEMENT FOR THE PROTOTYPE VERIFICATION TEST SITE

CATEGORY	INSTRUMENT	MASS	POWER
Remote Sensing	HIRS-2	32.3KG	22.8W
	AVHRR-2	28.7KG	26.2W
	SAGE-2	29.5KG	14.0W
	SMMR	52.5KG	60.0W
	SBUV	35.0KG	
	TOMS	31.0KG	12.0W
	ASAS		
	ERBE		
	SCANNER	29.0KG	
	NON-SCANNER	32.0KG	50.0W
	SCAT-A	224.0KG	309.0W
Additional In-Situ Sensors	CONTAMINATION		
	TEMPERATURE		
	PRESSURE		
	WIND VELOCITY		
	GAS SAMPLING		
	AEROSOL SAMPLING		
	PARTICLE CONTAMINATION		
Additional Ground-Based Sensors	RADIOSONDE		
	SOLAR FLUX		
	TEMPERATURE		
	PRESSURE		

The initial payload complement may be some subset of these instruments along with some ground-based sensors and some in-situ sensors. Later payloads could evolve by adding and deleting instruments as observational requirements and budgets dictate. The advanced solid-state array

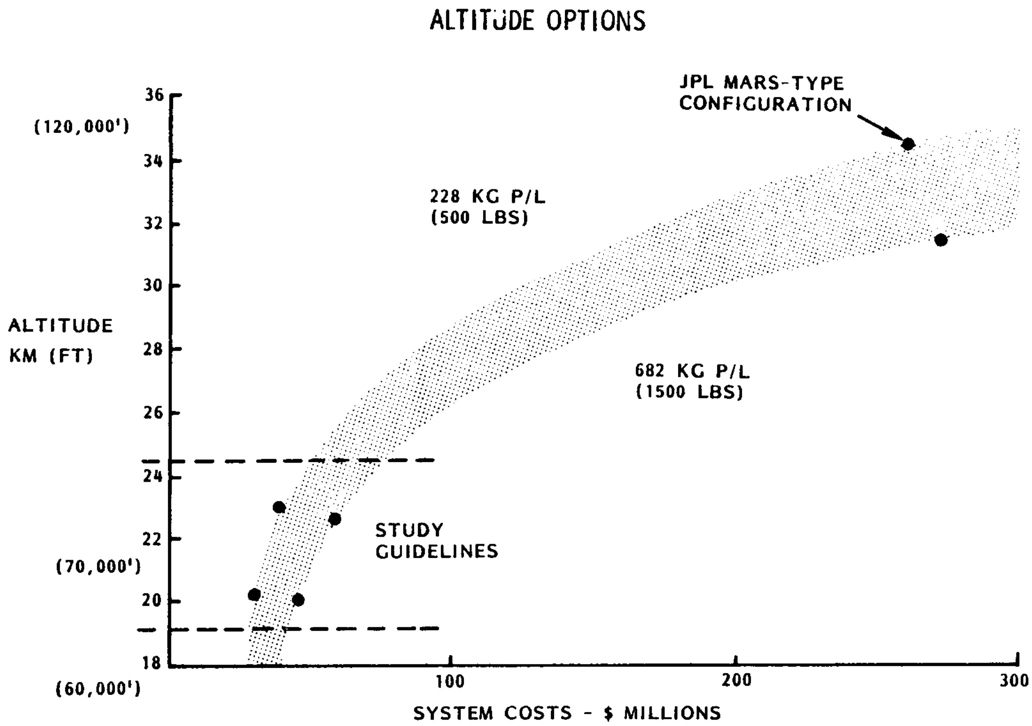


Figure 4. Altitude Options

spectroradiometer (ASAS) is an example of an existing sensor. Such instrumentation, if it can be acquired, could provide a low cost initial payload.

To summarize, instrumentation has been identified during this study which meets nearly all of the ODRs using Level I (currently available) instrumentation. Atmospheric CO (ODR 2), vertical cloud structure (ODR 7), and atmospheric surface pressure (ODR 18) require additional instrumentation. Ground based instruments may be useful for the latter ODR.

Summary of Ground and Platform Subsystem Study Results

Table 12 presents combinations of platform and ground subsystems that yield the least expensive options. Also shown are an indication of development readiness and total first system RDT&E cost in 1984 dollars to have an operational prototype by 1990.

In the post-1990 operational period, alternate power-source/platform configuration possibilities will be examined for cost-effective system options.

An efficient power source that would obviate many of the ground-based power subsystem problems/costs would be the use of the Solar Powered Satellite (SPS) system to beam microwave power down to the CO-OPS. This would necessitate only minor changes to the CO-OPS platform (i.e. rectenna, the microwave-receiving antenna, on the upper surface of the wing instead of the lower surface) and would remove the requirement for the massive and costly ground microwave power system. This corollary mission for the SPS should prove very cost-effective and give the CO-OPS a much more flexible and mobile flight path/range.

Conclusions and Recommendations

Lockheed, and its subcontractors, Raytheon, Ball Aerospace, and Sundstrand have unanimously concluded that the CO-OPS concept is certainly feasible within the technology, schedule, and cost considerations of the study. The required technologies of payload sensors, microwave transmission/ reception, platform capabilities, and data handling have all been demonstrated and can be synergistically combined to accomplish the CO-OPS prototype goals before 1990 and, at present estimates, well within the cost goal of $30 million.

Lockheed recommends that two primary systems be carried forward into Phase A. Those systems as shown in Table 12 are (1) wing with disk rectenna and slotted array with magnetrons and (3) wing rectenna and slotted array with magnetrons on a pedestal. Also recommended is a secondary system, (5) wing with disk rectenna and 4.5 meter disk with klystrons. These systems will give the following benefits:

- Systems 1 and 3 represent state-of-the-art systems with excellent development readiness characteristics and lowest cost.

TABLE 12. VIABLE COMBINATIONS OF GROUND AND PLATFORM SUBSYSTEMS

	PLATFORM SUBSYSTEM	RECTENNA MOUNT	ANTENNA TYPE	POWER TRANSMITTER	DEVELOPMENT READINESS	FIRST SYSTEM RDT&E COST ($M)
1.		DISK	SLOTTED ARRAY	MAGNETRONS	EXCELLENT	20.8
2.		WING	SLOTTED ARRAY	MAGNETRONS	EXCELLENT	21.0
3.	NOTE: WOLKOVITCH JOINED-	WING	SLOTTED ARRAY ON PEDESTALS	MAGNETRONS	EXCELLENT	23.5
4.	WINGS OR CONVEN- TIONAL CANTI-	DISK	SLOTTED ARRAY ON PEDESTALS	MAGNETRONS	EXCELLENT	24.6
5.	LEVERED WINGS ARE APPLICABLE	DISK	4.5 M DISHES	KLYSTRON	EXCELLENT	29.5
6.	TO ALL 10 CONFIGUR-	WING	4.5 M DISHES	KLYSTRON	EXCELLENT	30.24
7.	ATIONS.	WING	11 M DISHES	KLYSTRON	EXCELLENT-GOOD	34.8
8.		DISK	11 M DISHES	KLYSTRON	EXCELLENT-GOOD	35.4
9.		DISK	SLOTTED ARRAY	SOLID-STATE	GOOD	37.2
10.		WING	SLOTTED ARRAY	SOLID-STATE	GOOD	41.8

- Platform configurations for Systems 1 and 3 will provide valuable tradeoff information between a joined-wing and conventional cantilevered configuration.

- Systems 1 and 3 rectennas, wing and disk, will permit the evaluation and determination of the relative merits of each.

- Systems 1 and 3 ground power systems using a flat slotted array on pedestals and the same array on the ground will primarily be evaluated for the beam steering capability of each.

- System 5 will be investigated to the extent necessary to evaluate the operational advantages/disadvantages of antenna dishes and klystron power transmitters since 1 and 3 contain neither of these subsystem components. While this system costs more than the others, its costs are still within the study goal and we feel it should not be abandoned without further analysis in Phase A.

Lockheed is prepared to immediately initiate further planning activities with NASA Marshall, the Department of Energy, and the scientific user-community in order to ensure the timely and systematic progress of the CO-OPS program through the A, B, and CD phases, and into a productive, cost-effective data collection system. This report is internally identified as LG87ER0046.

1.0 INTRODUCTION

1.1 Background

Technologies leading to this Carbon-Dioxide Observational Platform System (CO-OPS) feasibility study had their origins in several space-oriented technology development programs begun in the 1960's. These programs developed flight hardware to monitor global climatological model parameters using satellites instrumented with multi-spectral scanners. Data gathering was limited to one of two modes:

- o Low resolution, continuous observations from geosynchronous orbit; or

- o Higher resolution, once per orbit observations from low earth orbit.

Observations have also been made using airborne sensors mounted on a variety of aircraft or on free-floating balloons. The former provided high resolution data for very short periods of time over one ground location. The latter provided high resolution data continuously, but not over the same ground location as balloons drifted with the air mass into which they were launched. Rocket probes have also been used to gather highly accurate short-duration localized data.

Each of these observation methods provided accurate, helpful data to scientists and meteorologists who were attempting to determine the long-term effects of carbon dioxide buildup in the earth's atmosphere. Space-borne packages had the disadvantage of requiring long lead-times, on the order of ten years from conception to operations. Once these space payloads were launched, observers were unable to change payloads if mission requirements changed. Four types of platforms to carry these sensors aloft have been used to date:

- o NASA/Lockheed U-2 and ER-1 aircraft capable of carrying sensors to around 21 km (70,000 feet) for periods of several hours;

- o Rocket-launched probes capable of reaching up to 40 km (131,200 feet) for periods of tens of minutes;

- o Free-flying balloons with sophisticated platforms onboard capable of sustaining altitudes of 37 km (121,360 feet) for days to months but only able to go with the prevailing winds aloft; and

- o Satellites either in low earth orbit or geosynchronous orbit.

None provided continuous, in-situ data, however, since this could only be done with an airborne platform capable of staying over one spot for very long periods of time. Other technologies advanced during the 1970's and early 1980's which would make possible a very long endurance airborne platform. These technologies were:

- o High efficiency microwave transmission and reception from a remote site, as studied in NASA/ MSFC Solar Power Satellite (SPS) Program done for the DOE;

- o Solar photovoltaic propulsion using space-qualified solar cells coupled with fuel cells for energy storage;

- o Large lightweight space structures capable of use in low speed airborne platforms; and

- o The Computer Revolution and its impact on the development of autonomous vehicles of all sorts.

It was the NASA Program, previously referred to, which identified CO-OPS as a near-term option to measure global climatological parameters and DOE selected it for further study. Studies done at several NASA centers, at other Government agencies in the U.S. and Canada and in industry have shown that a microwave powered airborne platform could be developed by the late 1980's and fielded with its ground power station to provide continuous in-situ measurements of global climatological model parameters over remote sites. During fiscal 1983 and 1984, NASA/MSFC conducted a systems study for DOE entitled "Utilization of Space For CO2 Research." Although this study was oriented toward space observations, DOE mentioned the potential of near-space geo-stationary platform systems to provide regional data to calibrate space-based sensors. Such a platform, NASA/MSFC postulated, could also be used to calibrate global climate models and to improve parametric algorithms characterizing regional and global data trends. For that reason, new specifically designed high-altitude observational systems are being sought. These new data could then be compared to data gathered by other methods which would provide benchmarks. The objective of this current study has been to determine the feasibility of such an observation system for a specific mission.

The DOE has had the charter within the U.S. Government for the last several years for monitoring the buildup of carbon dioxide in the earth's atmosphere. Considerable concern, borne out by Government research (Ref. 1) has been expressed about the buildup of carbon dioxide (CO_2) in the upper atmosphere and DOE has been attempting to monitor this in-situ with a variety of sensors. Each type of sensor platform has its benefits and its drawbacks. The major thread connecting all is that none is perfectly suited for highly accurate long-duration in-situ measurements of CO_2 over all areas of interest. The platforms which provide measurement accuracy (ER-1, probes, balloons and low earth orbit satellites) are not the ones which provide stationary positioning and the one which provides stationary positioning (geosynchronous satellite) compromises resolution to do so. DOE has determined that long-duration in-situ measurements are crucial to accurately determining the buildup of CO_2 in our atmosphere (Ref. 1).

1.2 The Concept of Microwave Powered Flight

High-altitude long endurance (HALE) flight is required to perform a variety of military and non-military missions such as those described in

Ref.s 4, 11, 12 and 13. Specific mission requirements will detail the altitude band necessary and a corresponding minimum or maximum endurance. These two mission parameters will play an important role in vehicle design. Regardless of specific mission details, though, some basic observations may be made about flight at high-altitudes for long periods of time.

Figure 5 shows the relationship of meteorological and atmospheric factors to design considerations. The upper left curve is a typical plot of wind speed as it varies with altitude. Exact values of wind speed to be used will be determined by mission location and time of year. In order to minimize power required, which is necessary to minimize fuel consumption and maximize time aloft, it is necessary to minimize airspeed. This can be done by flying at very high lift coefficients and at altitudes where wind speed is as low as possible, if holding a constant ground track is important. Altitudes at which winds are minimized are usually quite high and air densities are correspondingly low. The results of low air density, low airspeed and low power level yield aircraft configurations which characteristically have low power-to-mass ratios and low wing loadings, as shown by the arrow in the plot at lower right in Figure 5. This goes against the historical trend in which aircraft increase in both installed power-to-mass ratio and wing loading with time. Figure 6 shows this last plot in greater detail. The area in which microwave-powered aircraft fall is shown in the vicinity of the 1903 Wright Flyer.

Several types of regenerative (gathers energy from some renewable source) and non-regenerative (chemically fueled) powerplants exist for these vehicles. Few of these, though, are capable of maintaining an observational platform with payloads ranging from about 227 kg (500 lbf) to about 680 kg (1500 lbf) at great altitudes (18 to 25 km (59000 to 82000 feet)) for periods of more than one to two weeks. Only regenerative power trains are capable of maintaining an observational platform at high-altitudes for the time periods postulated to be necessary for long-term in-situ measurement of CO_2 (up to 60 to 90 days). Three propulsion schemes have been the subject of recent study by the authors and by others in the field. These are:

- Radio-isotopic power;
- Solar power; and
- Microwave power.

The first scheme, nuclear power, may be ruled out for now because of potential hazards and unavailability of suitable fuels (Ref. 14). There may be circumstances, however, where this power source would be viable. The second scheme, solar power, is only feasible for operation at low to mid-latitudes and considerable energy storage development work must be done before an operational solar powered aircraft becomes a reality (Ref. 12).

The third scheme, microwave power, has its drawbacks, too. But studies done by Morris (Ref. 15), Heyson (Ref. 16), Brown (Ref. 3), DeLaurier (Ref. 5), Jull (Ref.s 4 and 6) and Reynaud (Ref. 7) indicate that

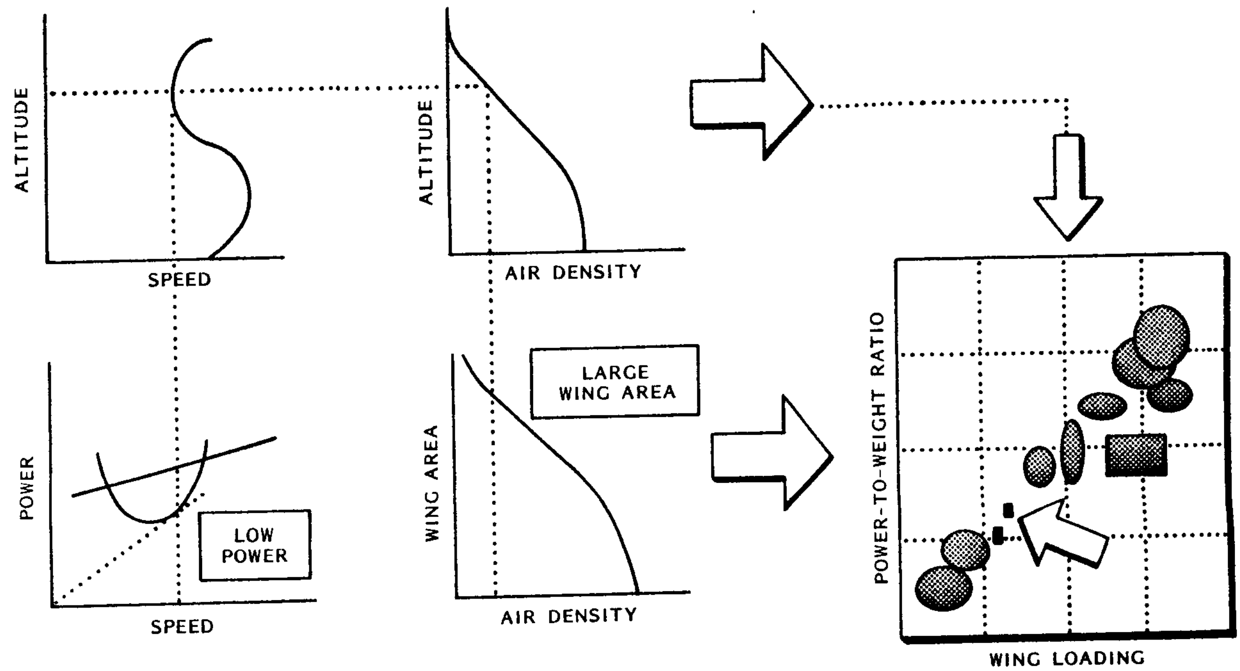


Figure 5. The Relationships of High Altitudes to Very Long Endurance

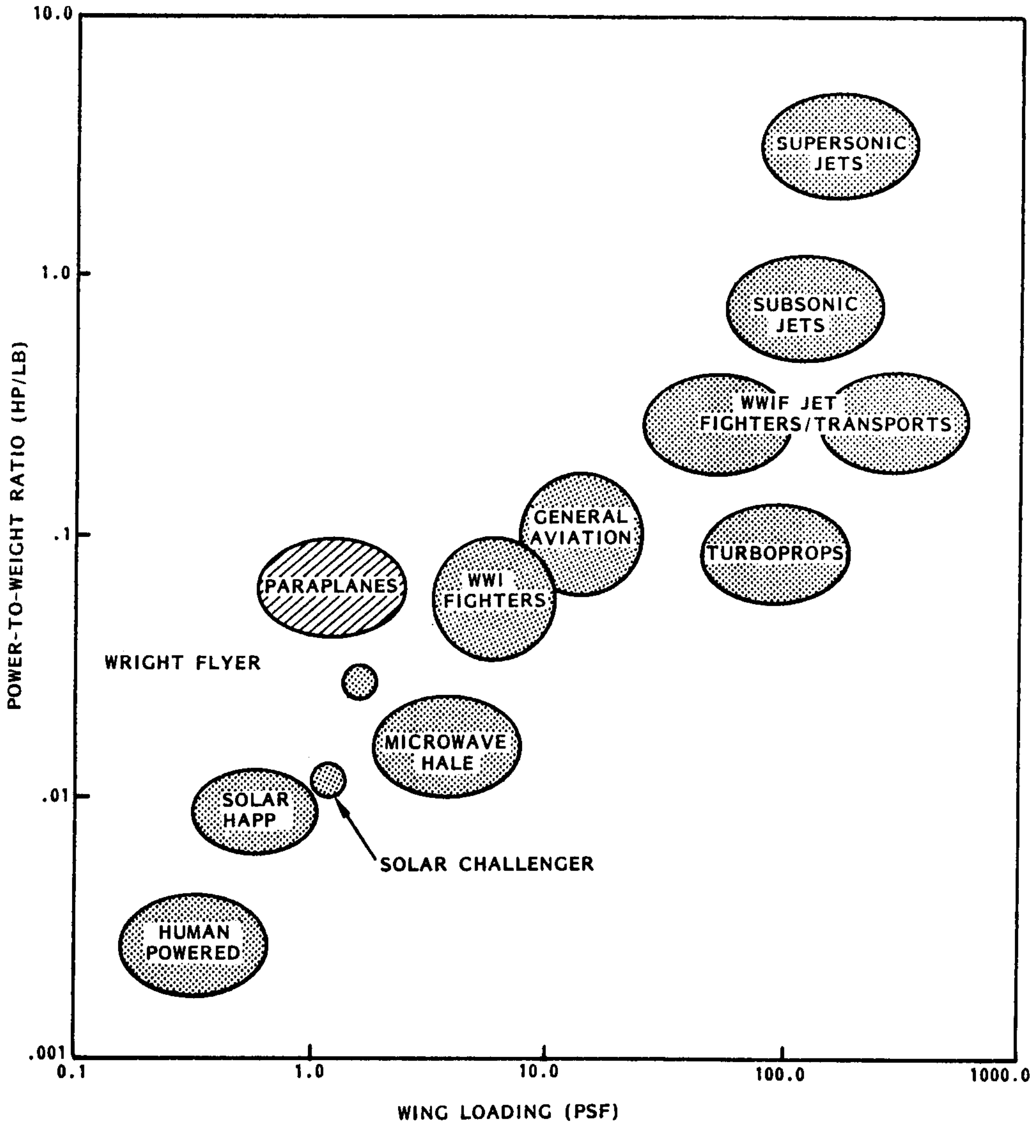


Figure 6. Historical Ranges of Power Loading and Wing Loading

it may be the only technically feasible HALE propulsion scheme available in the near-term; that is, within the next five to six years for operation over all areas of the globe at all times of year (Ref. 15).

This study addresses some of the interrelationships between the airborne portion of a HALE microwave propulsion system and its corresponding ground-based power source. Neither mission requirements nor variations in flight path due to winds aloft will be discussed. Both will be the subject of later work.

1.3 The Purpose of This Investigation

The objective of this study was to determine the feasibility of CO-OPS to satisfy near-term observational needs of the DOE CO2 Research Program. To do this, potential mission requirements that the DOE observational objectives impose on CO-OPS were determined. A system-level methodology was developed and used to determine the feasibility of a microwave powered CO-OP System for long-duration in-situ measurements of global climatological model parameters in a near-space environment. At the end of the study, recommendations were made as to the feasibility of CO-OPS and several promising concepts and missions were identified for further investigation. Finally, separate costs and programmatics were put together for development of the recommended CO-OPS concept or concepts. This information is in a separate volume to this report.

1.4 Scope

This study was eleven months in duration with nine months of technical work and two months for delivery of final documentation. During the course of the study, requirements which DOE observational objectives impose on a CO-OP System were defined. DOE, through NASA/MSFC provided the observational objectives and geographical locations for CO-OPS. Necessary parametric investigations of the feasibility of a microwave CO-OPS were then performed using a systems engineering approach to assure that all facets of the system are addressed. Recommendations as to feasibility were then made and concepts were recommended for further investigation. Last, costs and planning were done for development of a recommended CO-OPS concept within a five to six year time frame using existing technologies wherever possible.

Alternative propulsion schemes were examined briefly and compared to the baseline microwave system, which was the focus of this study. In this regard, previous work done for NASA, DoD, DOE and other agencies, which has been published in open literature, was assessed. The results of those studies were used wherever possible and were extrapolated upon to provide new data, moving forward from the existing database wherever possible.

Not within the scope of this study was the consideration of effects of the platform- and ground-subsystems on their environments, although limited assessment by Raytheon uncovered no major problems. Nor did this study investigate ways or costs of providing power to the ground subsystem once it is put into place as this was a study guideline.

2.0 TECHNICAL APPROACH

The technical approach used to achieve the objectives of this study was to (1) define the system characteristics required by the experimental packages and (2) using a generic system configuration, optimize the required system by methodical variations of subsystem configurations and operating parameters.

Previous studies done separately by the participating companies in this work have examined components of the system which could be utilized, such as airframe design technologies, efficient lightweight electric propulsion schemes, space-qualified payloads and high-power microwave beam technology. Results of these previous studies have been used where applicable to produce an optimum CO-OP System.

2.1 Systems Engineering

The systems approach used in this study is shown schematically in the Figure 7 below. In this approach, the basic system limitations and observational package requirements are examined and their impacts on system components are assessed. The central task to this study was Task 6, Systems Engineering and Integration. All other tasks fed into this or were derived from it. Each subsystem was characterized in such a way that effects of unique subsystem performance parameters could be related to the overall system. Likewise, components of each subsystem were interrelated to subsystem characteristics and, thence, to the overall system. This approach allowed examination of the effect of changes of typical subsystem design parameters on the overall system and assured a well-balanced system configuration as a result.

The unique nature of microwave powered platform design stems from the effects of ground subsystem power and radiating area on platform subsystem size, shape and orientation to the beam. To quantify these effects on system configurations a dedicated set of analytical tools was assembled. These tools related microwave power flux density available to antenna area, collector (rectenna) area and platform power train mass. The tools then reconciled these quantities with sizing, performance, and cost parameters for all subsystems.

2.2 Subsystem Interactions

There are several interesting interconnections between various subsystems. A relationship exists, for instance, between ground antenna area and rectenna area such that both must be carefully considered together in designing the overall system in order to minimize some system figure of merit such as cost. Microwave power is generated on the ground and collected at the platform with a receiving rectifier antenna (rectenna). The ability of the power transmission subsystem to operate effectively depends on the ability of the ground antenna to focus transmitted energy on the rectenna. The larger the required platform motion flexibility in terms of countering winds aloft or meeting payload data collection requirements,

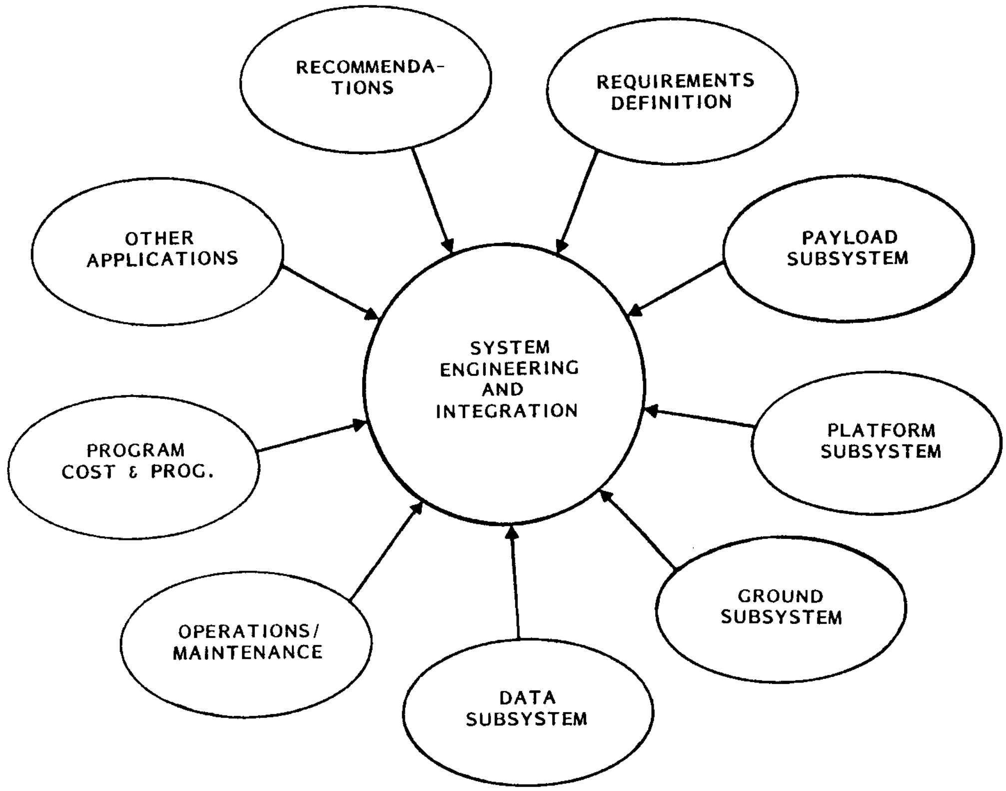


Figure 7. A Schematic of the System Engineering Used

the larger the degree of freedom required in the antenna control subsystem and the higher the ground subsystem cost.

Another interesting interconnection uncovered in recent work is the relationship between platform aerodynamic efficiency and microwave beam spot size. For a given spot size, two extremes of platform aerodynamic efficiency will yield comparable system efficiencies. A platform with a low aspect ratio wing will have a planform conducive to intercepting a larger percentage of the beam than a more aerodynamically efficient wing of the same area with a higher aspect ratio. To a point. That point is reached when platform aerodynamic efficiency becomes so high that it overcomes the need to intercept a large portion of the microwave beam.

The power control subsystem exists to focus the microwave beam on the platform rectenna. Transmitted power must be controlled to match load power since too much of a mismatch may damage rectenna elements. One way around this is to include on the platform some energy storage subsystem for load leveling. Having such a capability for energy storage onboard the platform, though, introduces a greater margin of safety in emergencies and allows excursions from the beam at times when winds aloft or mission requirements may dictate.

Once these subsystem interrelationships have been established in the system methodology, the overall system could be examined in detail. As iterations progressed, important subsystem design parameters were determined and several very capable CO-OP Systems resulted.

3.0 REQUIREMENTS DEFINITION

3.1 Overview

The first task done during this study was to define mission, payload, technology and cost requirements of subsystems and of the CO-OP System. Results were expressed as constraints and tests were applied at various points in a comprehensive system sizing methodology. In parallel with this work was a complete definition of possible payloads, which will be discussed in the next section. Discussed first will be the primary mission. Next will be other missions and applications which was Task 10 in the study plan shown earlier. The final paragraphs in this section will discuss system and subsystem requirements as applied to potential mission payload complements.

Primary Mission and Location

The purpose of CO-OPS is to verify system capability to operate in the upper atmosphere continuously for months at a time over a long period (up to 10 years). The system will be capable of operating at a variety of other sites with similar environmental conditions. The primary mission will take place at the prototype verification test site which will probably be NASA/Marshall Space Flight Center.

The potential recommended payload complement will be a variety of climatological sensors which will be detailed in later sections. All payloads have been considered user-supplied for costing purposes.

Other Applications and Utilizations

The CO-OP System is capable of fulfilling a variety of additional missions with little or no modification to either the platform or ground subsystems. Particularly interesting missions are discussed in the next four paragraphs.

Communications Relay. The first alternate mission to be discussed here is a communications relay mission which has applications to virtually every country in the world and to businesses which need low cost regional relay platforms. Flying at an altitude of 20 to 22 km (65 to 72 kfeet), a CO-OPS platform could retransmit radio, television, microwave or laser signals between points up to 1300 km (700 n.mi.) away. The Canadian Government has studied applications of microwave powered high-altitude relays for this application in the Stationary high-altitude Relay Platform (SHARP) program (Ref.s 4, 5, 6 and 7). SHARP design criteria can be applied to the CO-OP System to determine the feasibility of CO-OPS for this mission.

Weather Phenomenological Observation. A second interesting mission is weather observation. The CO-OPS platform could be instrumented for thunderstorm phenomenological observation and stationed either above a line of thunderstorms or off to one side. This mission is being studied at NASA/MSFC (Ref. 9) and could be demonstrated with a CO-OPS platform at the prototype verification test site. Additional instrumentation would add 22.7 kg (50 lbf) and a few watts to the CO-OPS prototype payload complement.

Off-shore Monitoring. A third potential ancillary mission is off-shore monitoring. The CO-OP System could orbit close to shorelines to observe shipping traffic within U.S. Territorial Waters and within the 200 n. mi. (371 km) fishing limit. Cruising at an altitude of 20 km, the radio horizon would be 556 kM (300 n. mi.) away. This mission has been studied by the U.S. Coast Guard (Ref. 28).

Forestry Observation. A fourth potential mission is forestry observation. The U.S. Forestry Service has an ongoing need to monitor the health of forested lands. One or more stationary CO-OPS platforms could monitor forests in the West and pass data between ground stations. Forests could be observed for general health as well as for fire prevention. Onboard sensors would also be capable of detecting the hottest spots in forest fires and platforms could provide targeting information to aerial bombers (Ref. 10).

3.2 Discussion of Observational Data Requirements for Each Site

The DOE has identified six categories of desired observations as part of their mandate to monitor the buildup of CO_2 in the atmosphere. These categories are presented in Table 13 below.

TABLE 13. CATEGORIES OF ATMOSPHERIC & EARTH OBSERVATIONS

CATEGORY	TOPIC
A	ATMOSPHERIC PROFILES
B	ATMOSPHERIC SPECIES
C	CLOUDS
D	SEA/OCEAN
E	SNOW/ICE
F	SURFACE CONDITIONS

Note that Category A, B, C and F measurements would apply at any observation site, while category D would apply only for an ocean site. Category E measurements would be of interest where snow and ice were the dominant surface cover.

The Observational Data Requirements (ODRs) are defined in Appendix B of the RFP which led to this study and are reproduced in Appendix A of this report. ODRs have been assigned numbers from 1 to 23 and have been correlated with the above categories in Table 14 below.

TABLE 14. CATEGORY-TO-OBSERVATIONAL DATA REQUIREMENT CORRELATIONS FOR THIS STUDY

	CATEGORY/TOPIC	ODR	OBSERVABLE
A:	ATMOSPHERIC PROFILES	21	VERTICAL TEMPERATURE PROFILE
		22	VERTICAL WATER VAPOR PROFILE
		23	WIND FIELD
B:	ATMOSPHERIC SPECIES	1	AEROSOL CONCENTRATION
		2	ATMOSPHERIC CONCENTRATIONS, CO
		3	ATMOSPHERIC CONCENTRATIONS, TRACE GASES
	ON-PLATFORM MEASUREMENTS:		A. TEMPERATURE, PRESSURE, AIRSPEED, GAS AND AEROSOL SAMPLING
			B. PARTICLE CONCENTRATIONS
C:	CLOUDS	5	CLOUDS, CIRRUS
		6	CLOUDS, FRACTIONAL COVERAGE
		7	CLOUDS, VERTICAL STRUCTURE
		10	RADIANCE AT TOP OF THE ATMOSPHERE
D:	SEA AND OCEAN	11	SEA CURRENTS
		12	SEA ICE
		13	SEA LEVEL
		14	SEA SURFACE TEMPERATURE
		15	SEA SURFACE WINDS
E:	SNOW AND ICE	8	LAND ICE
		16	SNOW COVER
F:	SURFACE CONDITIONS	4	BIOSPHERE, VEGETATION INDEX
		9	PRECIPITATION
		17	SURFACE ALBEDO
		18	SURFACE ATMOSPHERIC PRESSURE
		19	SURFACE MOISTURE, SOIL
		20	SURFACE TEMPERATURE, SOIL

Observation Sites

The DOE has identified five possible CO-OPS observation sites. These are presented below in order of descending emphasis in this study.

- Site 1, the prototype verification test site which will probably be NASA Marshall Space Flight Center;
- Site 2, either Vandenberg Air Force Base or Edwards Air Force Base;

- o Site 3, along the east coast in the New Jersey area;
- o Site 4, sites particularly suitable to measurement of carbon dioxide buildup such as the west antarctic, the intertropical zone (Panama) and the east coast north of 60° north latitude;
- o Site 5, any target of opportunity.

Site-to-ODR correlations are presented in Table 15 below. Also presented are the types of instrumentation required to make the observations indicated in Table 13. Thus, to identify the required payload complement for each observation site, compare the list of required instrumentation to the available instruments.

3.3 Some Interactions of Subsystem Design Requirements

Payload Effect on Platform Design

Payload factors affecting system ability to take continuous in-situ measurements duration are payload mass, drag producing payload attachment features such as viewing ports or fairings, and odd viewing angles for calibration. Features which create drag result from the need for instrument ports in the platform skin or bulges to hide unsightly lumps and corners. Viewing ports are required to ensure that the platform provides those interfaces required to achieve the second mission goal of observation. Required viewing ports will depend on the particular observation. NADIR viewing instruments and scanners looking through NADIR will require a clear view of earth. Limb viewing instruments will require a clear view of the earth's limb. Some limb scanners must observe the sun as it rises and sets and, hence, may determine platform flightpath during part of each day's mission. Solar viewing instruments must be able to continuously track the sun. Most instruments will frequently need to be calibrated by viewing either the sun and/or deep space. Platform structure must be excluded from the viewing envelope in all cases. To summarize, viewing requirements will be:

- o Placement of payload instruments on the platform in accordance with the viewing requirements of each payload instrument;
- o Careful coordination between the payload observation timeline and the operational timeline flightplan of the platform.

Payload viewing requirements may dictate modifications to the instruments, although such modifications could be costly and should be kept to a minimum.

To successfully make the required observations, payload contamination must be rigorously controlled. The necessity for contamination control will place requirements on the design and operation of the platform. Special protection of the payload will be required during all phases of the

TABLE 15. SITE-TO-OBSERVATIONAL DATA REQUIREMENTS CORRELATIONS FOR THIS STUDY

DESIRED SITE COVERAGE	CATEGORY	TOPIC	ODR	INSTRUMENTATION REQ'D
1,5 2,3 4	A	ATMOSPHERIC PROFILES	21	TEMPERATURE SOUNDER
			22	HUMIDITY SOUNDER
			23	RADAR SCATTEROMETER
	B	ATMOSPHERIC SPECIES	1	ACTIVE OR PASSIVE SPECTROMETERS
			2	IN-SITU PLATFORM SENSORS: A,B
	C	CLOUDS	5	TEMPERATURE SOUNDER/ RADIOMETER
			6	IMAGING RADIOMETER
			7	PARALLAX IMAGING SOUNDERS/RADIOMETERS
			10	TOTAL RADIATION MONITORS
	D	SEA AND OCEAN	11	ALTIMETER AND/OR OCEAN CHLOROPHYLL IMAGER
			12	HUMIDITY SOUNDER/ VISIBLE, NIR,IR IMAGER
			13	ALTIMETER
			14	TEMPERATURE SOUNDER, RADIOMETER
			15	ALTIMETER, RADAR SCATTEROMETER
	E	SNOW AND ICE	8	ALTIMETER
			16	HUMIDITY SOUNDER (MICROWAVE)
	F	SURFACE CONDITIONS	4	NIR RADIOMETER, SELECTED VEGETATION BANDS
			9	HUMIDITY SOUNDER
			17	VISIBLE RADIOMETER
			18	GROUND BASED SENSOR?
			19	MICROWAVE SOUNDER
			20	TEMPERATURE SOUNDER/ RADIOMETER

mission including preflight, climb to altitude, daily operations and during descent and recovery.

One of the major system cost drivers is the interaction of the diameter of the focused microwave power beam, or spot, relative to rectenna and platform geometries. At a nominal altitude of 20 km (65,600 feet), the microwave power spot from about 10 to 40 m (33 to 132 feet) in diameter, can vary depending upon the ground subsystem type and design that best suited each platform design considered. Power density, measured in watts per square meter, is the greatest at the center of this spot and decreases roughly logarithmically toward the edges. Useful power is usually considered to exist between the center and a radius established at the points where power has decreased to one-half the value at the center of the spot. This smaller circle is known as the half-power circle. It should ideally correspond to the diameter of a platform's disk rectenna. Diameter is then limited to the size of the half-power circle value. There is a corresponding ground antenna diameter to produce the required spot size for every ground power option.

There are a wide variety of platform subsystem shapes to carry the rectenna. These shapes may vary from a circular wing of just more than aspect ratio 1 and slightly larger than the half-power circle in diameter to a very efficient sailplane wing of very high aspect ratio. The highly efficient aerodynamic shape will require less power than a less efficient shape but will intercept less of a circular spot. Because less is intercepted by a highly efficient sailplane type wing, more power must be beamed up and more must be generated on the ground requiring a larger array. The tradeoff to be performed, then, is between highly efficient subsystems aloft and on the ground and less efficient subsystems optimized to work together to minimize total system cost. Platform subsystem configuration and ground subsystem options change the details of this trade, but not the basic logic.

3.4 System Mobility Requirements

The CO-OP System will be studied for the possibility of operation at more than one site. This will require defining and costing the disassembly, transportation and reassembly of the ground subsystem as well as parts of the data subsystem and platform subsystem support.

3.5 Flight Control Requirements

The flight control requirements will be dictated by two flight segments. The one requiring the highest control power is the emergency let-down and landing where favorable weather conditions cannot be chosen, as they can for take-off and climb-out operations. Specific control power requirements, times to achieve bank angles, and corresponding control surface deflection rates must be determined on a methodical basis through dynamic analyses of this flight segment.

4.0 PAYLOAD SUBSYSTEM

4.1 Overview

The payload subsystem task provided the needed inputs to accomplish the primary study objective which was to determine if long-term earth observation missions are technically feasible from a near-space geo-stationary monitoring platform. Interface requirements which impacted the ability of a platform configured to accommodate a typical applications payload had to be assessed first. These results were presented in the previous section.

The key issues involved in demonstrating feasibility of a CO-OP System are those that affect the ability of the system to achieve mission goals. The top-level mission goals are:

- Continuous in-situ measurements from one to three months at altitude;
- Capability of making a variety of earth, ocean and atmospheric measurements; and
- The system, and its subsystems, must be
  - portable
  - retrievable
  - redeployable and
  - capable of remote operation.

Many lower level mission goals follow from these. The study determined and addressed the issues which affected system feasibility to achieve these top-level goals.

Observational Data Requirements (ODRs) provided by users during the Ref. 1 study were used to select typical instrument complements. The ODRs appear in several tables in this section and in Appendix A. These complements then allowed determination of required platform interfaces for a wide assortment of payloads. Final selection of a specific instrument complement will be the topic of future studies and must have a strong input from the end-user community.

Figure 8 presents the study plan for the payload subsystem determination task. The sub-tasks shown are:

- Identify types of measurements that must be made;
- Identify types of instruments needed to make these measurements;
- Select candidate instruments based on earlier studies (Ref.s 1, 16 and 27);
- Identify platform and payload characteristics required to accomplish the measurements;

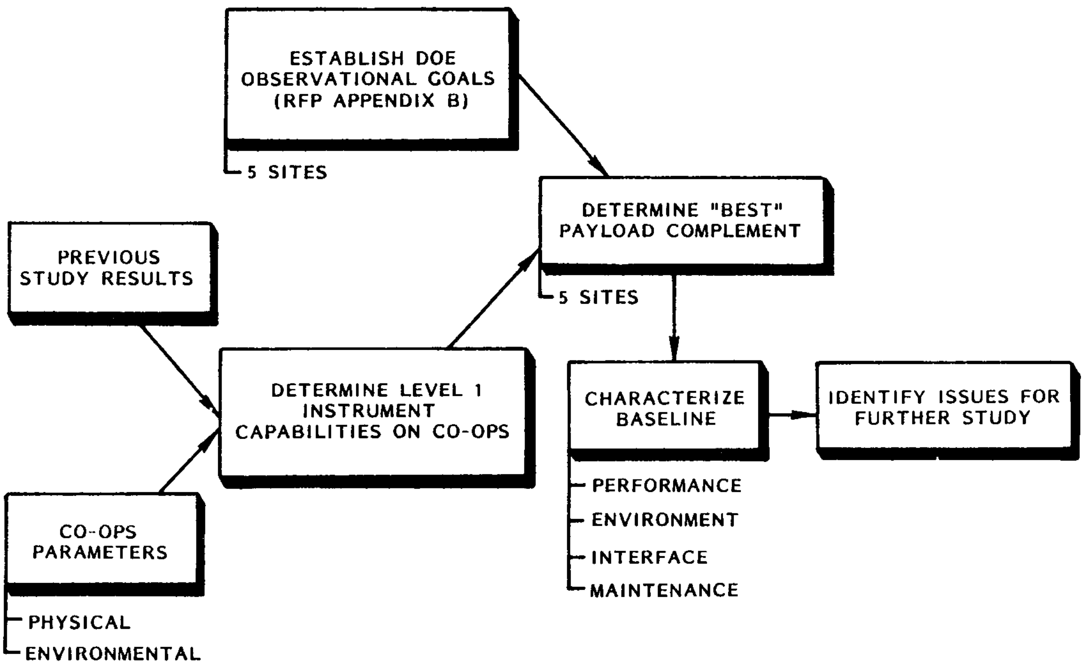


Figure 8. Payload Subsystem Study Plan

- o Iterate through system considerations to configure one or more suitable platforms;

- o Identify issues for further study; and

- o Document the results.

4.2 Effect of S.O.T.A. on Choice of Payload Package

Available instruments were defined by the RFP to be those designated Level I in Ref. 1. Level I instruments are those which require no new development and have flown in space. It should be noted that some of these instruments were built several years ago and, hence, may be difficult to reprocure because of their obsolescent technology. These instruments are listed and described in Appendix A of this report. In addition, other instruments which have flown since Ref. 1 was written have been considered as has instrumentation developed specifically for use on aircraft. Figure 9 summarizes the instrument data base examined in Ref. 1. Of the 27 instruments presented, approximately 19 are Level I. Some designated Level II at the time of the study are Level I now. Other instruments which may be of interest are not included. The instruments range in mass from 9 kg to 270 kg (20 to 600 lbf) and in power required from 2.5 to 435 watts. These ranges were used in system modeling which will be discussed in later sections. These payloads exhibited a power-to-mass ratio of approximately 0.92 1 0.38 watts/kg.

4.3 Selection of A Typical Payload Complement

Comparison of Instrumentation--Required versus Available

Once required and available instrumentation had been defined, the two groups could be compared to identify a potential payload complement. The goal of this comparison was to determine:

- o Minimum instrument complement for each observation site;

- o Where observational holes existed;

- o Logical hierarchy for payload expansion.

The resulting allocation of instruments is summarized in Table 16 which shows that almost all of the ODRs can be met simultaneously by using an instrument complement consisting of several Level I or equivalent instruments. The table also shows that a hierarchical approach to instrument selection is feasible. A complement of instruments can be selected to satisfy most of the ODRs for Sites #1 and #5. A few instruments can be added to this complement to achieve the additional ODR requirements needed for sites #2 and #3. This latter complement will also meet the ODRs for Site #4.

27 INSTRUMENTS:
● APPROXIMATELY 19 ARE LEVEL I ● OMITS SOME OTHERS WHICH MAY BE OF INTEREST -- ERBE -- AIRCRAFT-QUALIFIED INSTRUMENTS
SUMMARY OF LEVEL INSTRUMENTS:
● RANGE IN MASS FROM 9 KG (SSU) TO 270 KB (TM) ● RANGE IN POWER FROM 2.5 WATTS (SAGE I) TO 435 WATTS (ATMOS) ● POWER-TO-MASS RATIO IS 0.92 1 0.38 WATTS/KG
LEVEL 1 INSTRUMENTS HAVE BEEN DEVELOPED AND FLOWN, REBUILD STATUS IS:
● TO BE DETERMINED IN PHASE A ● SPECIFIC TO INSTRUMENT

Figure 9. Summary of the Instrument Data Base Considered During This Study

TABLE 16. ALLOCATION OF INSTRUMENTS FOR CO-OPS ODR & MISSION CATEGORIES

SITE CATEGORY	CATEGORY	SDR #	HIRS-2	AVHRR-2	SAGE/2	SMMR	LANDSAT MLA	SBUV/TOMS	ALT	ATMOS	ERBE-NS-S	CZCS/OCI	LIDAR	SCAT	ASAS	THIR	COMMENTS
I SITES #1.5 1) NASA/MSFC 5) "TARGET OF OPPORTUNITY"	A	21	x														
		22	x			x											
		23												x			
	B	1			x												ALSO MONITOR TOTAL SOLAR FLUX ON GROUND
		2								x			x				ATMOS OR LASER HETERODYNE (LHS) OR LIMB SCAN RADIOMETER
		3						x		x							O_3 ONLY WITHOUT ATMOS, LHS, OR LIMB SCANNING RADIOMETER
		A															
		B															
	C	5	x	x													
		6														x	
		7	x(?)														PARALLAX SENSOR REQUIRED
		10		x							x						
	F	9				x											
		17		x			?				x						
		18															GROUND BASED PRESSURE MONITOR
		19				x											
		20	x	x		x						x					
		4		x			x								x		
II SITES #2.3 2) VAFB/EAFB 3) EAST COAST	D	11							x			x			x		
		12				x	x					x			x		
		13							x								
		14	x	x		x						x					
		15							x					x	?		
III SITE #4 4) WEST ANTARTIC INTERTROPICAL ZONE EAST COAST @ 60° NORTH LATITUDE	E	8							x					x	?		
		16				x	x								x		

Some ODRs are difficult to satisfy with Level I instruments. The ODR #2, ATMOSPHERIC CO2 CONCENTRATION, requires the use of a high resolution spectrometer such as ATMOS or LIMB SCANNING RADIOMETER, or an active spectrometer such as LASER HETERODYNE. These are large, complicated instruments and are not recommended for CO-OPS at this time. The ODR #7, VERTICAL CLOUD STRUCTURE, requires a parallax sensor. A ground based pressure monitor would be best for monitoring ground pressure.

The list of instruments in Table 16 was further condensed to arrive at the recommended complements which will be discussed in the following paragraphs.

Site 1 and 5 Initial Payload and Site 2,3,4 Additional Payload

Based on these tradeoffs, the instrument complement listed in Table 17 below would permit satisfaction of almost all of these instruments. Assuming a hierarchical approach to acquisition of the instruments, the complement for initial Site #1 observations would consist of some subset of the listed instruments. Planning by users active in these fields of research is required to select the best instruments. This complement would also satisfy the ODRs for Site #5. The addition of two instruments to this complement, the CZCS/OCI ocean spectral imager and the ALT altimeter, would permit satisfaction of the ODRs for all the additional sites discussed here.

Further Desired Instrumentation. Table 18 lists some specific instruments that would be needed to satisfy the remaining ODRs. In addition, an assortment of in-situ monitors should be included on the platform and some ground based monitors should be included in the mission.

4.4 Characterization of Payload Subsystem Options

Site #1 Payload Characteristics

Table 19 summarizes the characteristics of the instruments that have been identified here as candidates for CO-OPS missions. The total mass and power for all of the listed "Category I" (Sites #1 and #5) instruments, not including SCAT-A and THIR, are 269.3 kg (594 lbf) and 131 watts. The initial payload complement would be some subset of these instruments along with some ground based sensors and some platform based sensors. Later payloads would evolve by adding and deleting instruments as observational requirements and budgets dictate. The advanced solid-state array spectroradiometer (ASAS) is an example of an existing airborne sensor. Such instrumentation, if it can be acquired, could provide low-cost initial instrumentation.

TABLE 17. SUMMARY OF INSTRUMENT COMPLEMENTS

INSTRUMENT	INSTRUMENT CAPABILITY
HIRS-2 (HIGH RESOLUTION INFRARED ER-2) PROFILE	TEMPERATURE SOUNDING AND SOUND WATER VAPOR
AVHRR-2 (ADVANCED VERY HIGH UTION RADIOMETER-2)	VISIBLE, NIR, IR IMAGING RESOL RADIOMETER
SAGE-2 (STRATOSPHERIC AEROSOL AND GAS EXPERIMENT-2)	AEROSOL AND GAS MEASUREMENT AT LIMB
SMMR (SCANNING MULTI-CHANNEL MICROWAVE RADIOMETER)	HUMIDITY SOUNDING ICE AND WIND
SBUV/TOMS (SOLAR BACKSCATTER ULTRAVIOLET RADIOMETER-TOTAL OZONE MAPPING SPECTROMETER)	OZONE PROFILE UV SOLAR IRRADIANCE
ERBE (EARTH RADIATION BUDGET EXPERIMENT)	
NON-SCANNER	SOLAR OUTPUT
SCANNER	EARTH RADIATION IN THREE BANDS: -TOTAL (0.2 TO 50 MICROMETERS) -SHORT WAVE (0.2 TO 5 MICROMETERS -LONG WAVE (5 TO 50 MICROMETERS)
SCAT (SCATTEROMETER)	WIND FIELD, BOTH SPEED AND DIRECTION
ASAS (ADVANCED SOLID-STATE ARRAY SPECTRORADIOMETER)	SILICON CHARGE-COUPLED DEVICE PUSHBROOM IMAGING SPECTRORADIOMETER
THIR (TEMPERATURE, HUMIDITY INFRARED RADIOMETER)	IMAGING TEMPERATURE AND HUMIDITY RADIOMETER CLOUDS, WATER VAPOR
ADDITIONS FOR SITES # 2,3 AND 4	
ALT (ALTIMETER)	RADAR ALTIMETER
CZCS/OCI (COASTAL ZONE COLOR SCANNER/OCEAN COLOR IMAGER)	OCEAN SURFACE CHARACTERISTICS SURFACE TEMPERATURE

TABLE 18. FURTHER DESIRED INSTRUMENTATION

INSTRUMENT	ADDED CAPABILITY
ATMOS, LASER HETERODYNE SPECTROMETER OR LIMB SCANNING SPECTROMETER	CARBON DIOXIDE AND TRACE GASES (ODR 2,3)
PARALLAX SENSOR	CLOUD VERTICAL STRUCTURE (ODR 7)
IN-SITU MONITORS ON PLATFORM	TEMPERATURE PRESSURE WIND VELOCITY GAS AND AEROSOL SAMPLING PARTICLE CONCENTRATIONS
GROUND BASED MONITORS	SOLAR FLUX MONITOR PLATFORM ALTITUDE, ORIENTATION, DIRECTION OF FLIGHT, SPEED AIR PRESSURE

TABLE 19. SUMMARY OF KEY PARAMETERS

CATEGORY	INSTRUMENT	WEIGHT	POWER	DATA RATE	SIZE (CM)	IFOV	FOV	OTHER
I	HIRS-2	32.3KG	22.8W		65x40.4 x35.3	15MRAD 300M	0.955 RAD	
	AVHRR-2	28.7KG	26.2W		76.8x28.4 x36.4	1.3x1.3MRAD 26M	1.33 RAD 112°(?)	
	SAGE-2	29.5KG	14W		38.7φx69.5 24x25x33 (ELECTRICAL)	1KM (ALTITUDINAL)		
	SMMR	52.3KG	60W		15.3x33x20.4 15.3x33x20.4 15.4x16.5x 70.4 80CMφ ANT.	0.8° - 4.2°	±25°	80CMφ ANTENNAS
	SBUV	35.5KG	12W		31x36x51	0.2x0.2RAD		
	TOMS	≈30KG				3°x3°		
	THIR							
	ERBE							
	SCANNER	29KG	50W		50φx60			
	NON-SCANNER	32KG			70φx60	FULL EARTH	FULL EARTH	
	SCAT-A	224KG	309W		0.7M³			SIX ANTENNAS
	ASAS							
IN-SITU	CONTAMINATION							
	TEMPERATURE							
	PRESSURE							
	WIND VELOCITY							
	GAS SAMPLING							
	AEROSOL SAMPLING							
	PARTICLE CONTAMINATION							
GROUND BASED SENSOR	RADIOSONDE							
	SOLAR FLUX							
	TEMPERATURE							
	PRESSURE							
II & III	CZCS	42KG	48W		78x53x37	.865x.865MRAD	1.37 RAD	
	OR							
	OCI	57KG	60W		56x41x87	1.3x1.3MRAD	1.45 RAD	
	ALT	93.8KG	164W		0.75M³			1M ANTENNA

Key Interface Requirements

Key interface problems which would affect platform feasibility were identified as part of this study. Figure 10 lists the major impacts that payloads will place on the platform subsystem configuration or on operations. Items listed affect lifetime, operations, platform configuration, or require payload modifications.

Since the system concept envisioned in this study uses microwave electromagnetic waves as a power source, the instruments must operate while being bathed with relatively high levels of microwave energy. Since this environment could cause significant errors in the measured outputs of the instruments in question, the feasibility of suppressing the environment at the instruments was examined in some detail. The assumed field level was 1000 volts/meter which corresponds to energy levels of about 2500 watts/square meter at the platform. Generally in all designs, steps must be taken to provide for microwave shielding. The fields discussed here are 180dB micro-volts. This results in a hostile environment 1000 times greater. The following problems could occur:

- o Desensitization due to rectification;
- o Heating due to I X R drop;
- o Offsets;
- o Poor response characteristics; and/or
- o Crystal or diode burnout.

The schematic in Figure 11 summarizes some preventive measures and design considerations which can be incorporated into instrument designs to eliminate the effects of microwave interference. These are:

THOSE THAT AFFECT MISSION DURATION (MASS AND DRAG):
● PAYLOAD DEFINITION AND TRADEOFFS ● VIEWING PORTS __ NADIR __ SOLAR __ DEEP SPACE __ EXCLUDE VIEW OF PLATFORM STRUCTURE ● PAYLOAD PLACEMENT ON PLATFORM ● COORDINATION OF PAYLOAD OBSERVATION TIMELINE AND OPERATIONAL FLIGHT PLAN TIMELINE ● MINIMIZE INSTRUMENT MODIFICATION
CONTAMINATION CONTROL:
● DESIGN AND OPERATION OF PLATFORM ● PROTECT PAYLOAD DURING ALL PHASES OF MISSION ● PRECLUDE PAYLOAD OR VIEWING PORTS ICING UP ● MICROWAVE FIELD ATTENUATION
RADIATIVE COOLER ISSUES AND ALTERNATIVES:
● EFFICACY __ ATMOSPHERIC EMISSION __ EARTHSHINE __ CONTAMINATION WINDOW EMISSION ● STORED CRYOGEN

Figure 10. Key Payload Subsystem Issues Affecting the CO-OP System

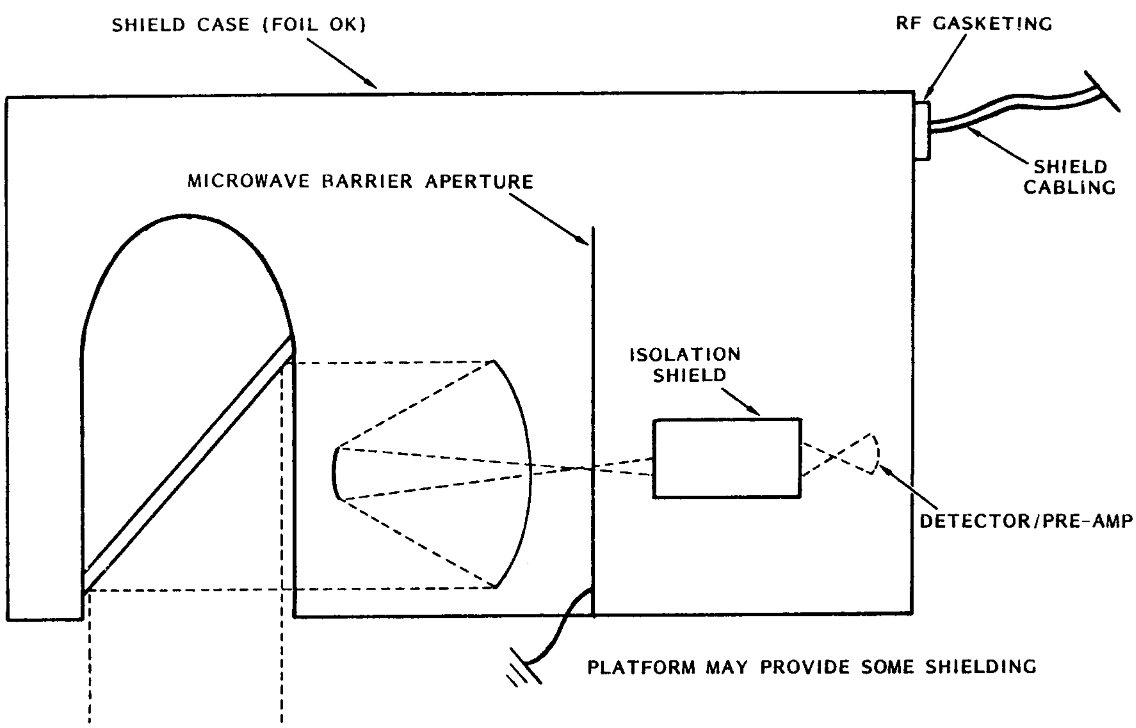


Figure 11. Preventing Deteriorative Effects of the Microwave Environment

- Shield the instrument cases and use RF gasketing so there is no aperture greater than one-twentieth of a wavelength at 2.45 ghz;

- Shield all external cabling;

- Consider shielding provided by platform structure;

- Where possible, design barriers into instruments using apertures which filter and reject microwave fields entering the telescope aperture and keep these fields from critical detector/pre-amps;

- Design detectors and readouts with isolation shielding as much as possible; and

- Limit the bandwidth of amplifiers as much as possible.

These modifications deserve significant attention during Phase A, Conceptual Design, at which time each potential instrument will be examined to determine design changes needed.

Detailed interfaces between the payload and the platform subsystems were not determined during this study. Instead, the payload-to-platform interfaces were addressed from a conceptual standpoint. Since the payloads require a large view to space and to the ground, a payload complement that mounts at the front of the platform fuselage in an open cavity may be assumed. The cavity would be covered during ascent and descent to afford contamination protection. The cover would be removed at altitude to permit a clear view for the instruments to their respective viewing targets.

Details of the payload-to-platform interface will be determined during the forthcoming Phase A study. This interface will place constraints on both the operation of the payload and the operation of the platform. Duty cycling of the payloads in the performance of their observational measurements must be coordinated and synchronized with platform heading and flightpath requirements. The platform will provide contamination protection for the payloads and may also contribute to providing protection for the payloads from the microwave environment. The platform will provide data buffering and storage for the payloads and will provide the capability to transmit payload data to the ground.

Payload Environment Requirements

The payloads mounted on the CO-OPS platform will require protection from various environmental factors. Those of interest include those encountered on the ground during storage, during integration of the payloads, as the platform is being launched and while it is in transit to operational altitude. In addition, payloads must tolerate and be compatible with the environment at operational altitude. When the platform is recovered, payloads must survive the recovery process. Payloads must then be protected from adverse environments while on the ground.

The environments of interest for payloads include thermal, EMI, microwave and contamination. The tolerable thermal environment depends upon the instrument in question but typically needs to be in a temperature range near ground ambient (20 centigrade) during operation. The storage temperature environment can exceed this range safely but, again, the tolerable environment depends upon the individual instrument. Typical storage environment temperature ranges could be as wide as from less than 0 centigrade to as warm as 50 centigrade.

A major task of the forthcoming Phase A study will be to determine the tolerable temperature environment for each individual instrument in the payload complement.

Payloads must be protected from EMI and microwave environments. Protection options were discussed in an earlier section.

Protection from contamination is very critical to ensure proper operation of instruments in the payload complement. Payloads consist of a series of instruments, all of which have critical optical and detector surfaces that must be protected from contamination in order for the instruments to perform properly. The need to protect from contamination will require adequate sheltering of the instrument while on the ground as well as in transit to altitude. While at altitude, the instruments must be protected from ambient contamination and the platform itself must be clean and as contamination-free as possible. Cryogenic surfaces in the instruments may condense ambient constituents such as water by freezing them out of the air. This must be designed against by not allowing any cold surface to be exposed to the ambient environment.

This pre-Phase A study uncovered that the environment at altitude contains a large amount of ozone. In fact, ozone concentration tends to peak near the operational altitude. The effect of ozone on structural and detector and optical materials during long-term exposure at present is unknown and deserves further study.

Viewing Angles

At operational altitude the individual instruments in the payload must be able to view their respective target scenes as well as calibration sources. Typically, most of the instruments are ground-looking during data acquisition. Those instruments need a clear view of the ground in order to adequately record their desired measurements. Structure from the platform as well as from other instruments cannot be allowed to be within the field-of-view of these instruments. Since the field-of-view is typically scanned across the earth, the result is a rather wide envelope that must be free of platform structure.

Some instruments in the anticipated complement must be able to view the sun during sunrise and sunset in order to make required measurements. These instruments use a solar occultation technique to monitor trace gases in the atmosphere. As with ground-viewing instruments, these instruments must not have structure within their fields-of-view as they are viewing the rising and setting sun. These constraints may determine the direction of flight during the measurements. The effect is that the operational constraints of the flying platform must conform, or be made to conform, with the observational constraints that the instruments place upon them.

In addition, almost all of the instruments will need to be able to view calibration sources external to the instrument. Typical calibration sources which may be used are the sun, deep space, or a diffuser that is illuminated by the sun. In order to view these sources the instruments must be able to scan and point at the source with no structure from the platform in its field-of-view. This will place constraints on platform configuration as well as operations. As the platform is being defined during Phase A, these considerations will be taken into account.

Data Requirements

The platform portion of the data subsystem must be able to accommodate the data requirements of the instrument payload complement. Actual data capacity required will depend upon which individual instruments form the complement as well as the operational viewing sequence of the instruments. By duty cycling the various instruments the overall instantaneous data rate required to be stored and transmitted can be averaged to a lower value than if the instruments are operated all the time.

An estimate of the required data rate was made as part of this study. Considering the Level I instruments that were derived to be a part of the initial Site 1 payload complement, the data rate required for the instruments when used in orbit is in the vicinity of 700 000 bits per second. This is a worst case number derived by adding individual instrument data rates and does not take into account any duty cycling that may occur. It should be noted that one of the instruments, the AVHRR/2, accounts for approximately 665 kbits/second. The CO-OPS platform data subsystem does not require a data rate capacity of this magnitude. This is because current instruments are designed to operate at earth orbital velocity. In the CO-OPS application they will operate at a velocity that is approximately a factor of 185 times less than orbital velocity. This means that the data acquired may be heavily oversampled for some applications. Hence, the acquired data rate may be approximately a factor of 200 less than orbital data rate although it is possible that some users may require more.

To size the data subsystem in a preliminary sense, this study took into account the addition of the Coastal Zone Color Scanner (CZCS) which will fly on the platform as part of an ocean-viewing mission. The CZCS instrument has a maximum orbital data rate of approximately 3500 kbits/second. By reducing this data rate by a factor of 200, a derived requirement for data rate capacity of 17 kbits/second may be estimated. To permit some margin, the design data rate value was taken to be 30 kbits/second.

During Phase A the technique to implement data rate reduction must be defined. Several options were discussed in this study. These options are:

- o Redesign the instruments to slow down the data rate;
- o Record only 1/200th of the actual data; or
- o Buffer the data as it comes out of the instrument and store it onboard. The data would then be averaged onboard, in memory, and transmitted to ground at the slower averaged data rate,
- o Downlink all the data.

This third option appears to be the most advantageous for the platform subsystem and does not require redesign of the instrument as would be the cased if the data rate coming out of the instrument were slowed.

Operational Altitude Requirements

This study assumed that the platform was operating nominally at 20 km (65 600 feet) altitude.

Frequency of Operations

This study did not address in detail the operational sequences needed by the instruments. These must be addressed during Phase A and will place operational constraints on the platform. In addition, the platform will place operational constraints on the instruments.

5.0 PLATFORM SUBSYSTEM SIZING METHODOLOGY

5.1 Overview

The purpose of this CO-OPS study was to determine the feasibility of a microwave-powered observation system and not just the platform (the technology for which is well in hand in the U.S. aerospace industry). In order to model the entire system, each piece, or subsystem, had to be analytically described. This section discusses the methodology used to describe the platform subsystem consisting of the aircraft configuration, its aerodynamics, its structure, its controls, and its power requirements. The primary power train will be discussed in a later section.

The methodology used here was developed to allow system designers maximum flexibility in analyzing and choosing configuration options. Thus, methods applied are very general and intended to estimate major design parameters within 10 to 20%. Pieces of these methods have been used in previous high-altitude aircraft conceptual design studies at Lockheed since 1980. Several will be described briefly here.

5.2 Candidate Configurations

A wide variety of configurations was examined during this feasibility study. These included both heavier-than-air and lighter-than-air alternatives as well as three generic fixed-wing configurations. Fixed-wing configurations were:

- A conventional monoplane with a wing-mounted rectenna;
- A conventional monoplane with a disk-mounted rectenna beneath the fuselage; and
- A joined wing.

Before discussing each of these configuration alternatives, a few words should be said about lighter-than-air ships. General platform sizing methodology will then be discussed.

Several studies have been done in recent years on applications of airships to a wide variety of civilian and military missions (Ref.s 2, 23, and 37). This work was reviewed during this study and some conclusions reached about the applicability of airships to CO-OPS missions. Ref. 2 postulated a semi-rigid high-altitude long endurance airship for a military mission with payload, time-on-station, and airspeed comparable to the primary CO-OPS mission. The airship was around 180 m (600 feet) in length, had a non-buoyant takeoff gross mass of around 12 000 kg (26 000 lbf) and required up to 155 kw (208 HP) of thrust power. Its volume was around 42000 cubic meters (1.5 million cubic feet), making it larger than the Goodyear airships by a considerable margin. In addition, all sources pointed out some generic problems with high-altitude airships:

- Large diurnal effect. Internal gases expand and contract daily requiring frequent management.
- Significant launch problems requiring further development;
- Airships tend to get larger with increasing speed; and
- Thrust power required increases with both size and speed.

For these reasons, airships were not considered feasible for the CO-OPS missions.

Configuration Geometry Methodology

A vital part of this platform sizing methodology is a physical description of the generic configuration being analyzed. This description needn't be detailed, but must include auxiliary flying surfaces, a fuselage and any nacelles or drag producing appendages. By skillful selection of initializing parameters, a wide variety of generic configurations can be modeled. The default configuration used here is one wing, an aft horizontal tail, a dorsal vertical and a long, thin fuselage connecting wing to horizontal and vertical stabilizers. The fuselage extends ahead of the wing and either one tractor propeller or two pusher propellers is assumed.

Basic geometry may be calculated for any type of configuration by specifying general physical platform parameters such as wingspan, wing taper ratio, wing aspect ratio and takeoff gross mass along with performance such as cruise altitude and airspeed. Given wing area, aspect ratio and taper ratio, root chord may be calculated followed by mean geometric chord. Given altitude, airspeed and takeoff gross mass, aircraft lift coefficient may then be calculated. If the aircraft is in turning flight, lift coefficient may be adjusted by dividing it by the cosine of the bank angle, which is calculated from previously specified altitude, airspeed and turn radius.

Next, horizontal and vertical tail arms and aspect ratios may be set to values typical of past high-altitude configurations done for other programs since 1980. Tail arms for both surfaces are for mean geometric chords. The horizontal tail aspect ratio is six and the vertical tail aspect ratio is three. These values are then used to calculate spans, areas, root chords and mean chords for both the horizontal and vertical. Taper ratios of these surfaces are the same as for the wing.

Candidate Configurations

Conventional Layout with Disk-Mounted Rectenna. The first of three basic configuration types modeled during this study represents a clean aerodynamic shape carrying a circular rectenna which is allowed to grow to a large fraction of wing reference area (rectenna area is held to 65% of platform wing area). This generic configuration was also examined by the

Canadian Department of Communications in their ongoing Stationary high-altitude Research Platform (SHARP) program (Ref.s 4, 5, 6 and 7). Figure 12 presents a typical disk-mounted rectenna platform configuration.

Conventional Layout with Wing-Mounted Rectenna. The second generic configuration examined is a conventional aircraft with a rectenna mounted on the wing undersurface. Configuration parameters modeled represent both ends of a spectrum of possible platforms. In one case, the platform is made as aerodynamically clean as possible at the expense of microwave reception. At the other, platform aerodynamic cleanliness is compromised to see if total first system RDT&E cost can be lowered. Propellers are placed aft to keep vortices from interfering with the lift distribution on the wing. The rectenna is conformal to the undersurface of a tapered wing and can be no larger than about 65% of wing reference area. This 65% is referred to as the rectenna packing factor and is one criterion applied to parametric analyses which will be discussed in section 9.5. The 65% upper limit on relative rectenna area allows for non-flat portions of the wing undersurface occupied by leading and trailing edges, wing fillets and control surfaces. Figure 13 presents a typical platform configuration with a wing-mounted rectenna.

Joined Wing. The third generic configuration is a joined wing which has been developed by Dr. Julian Wolkovitch of ACA Industries (Ref. 26) and has weight-saving and aerodynamic properties which may make it particularly applicable to the CO-OPS mission. It is a compromise between the two extremes just discussed in that a large amount of undersurface area is available for rectenna even though the platform is aerodynamically quite clean. Figure 14 presents a typical joined wing configuration.

5.3 Aerodynamic Characterization of Platforms

Platform Drag, C_D

The CO-OP System sizing methodology has been based wherever possible on accepted industry design practices. Methods in several technical subject areas had to be modified, however, to adjust industry practice to specific high-altitude long endurance platform characteristics. One of these areas is in calculation of platform drag coefficient. This dimensionless number is a measure of aerodynamic cleanliness. Drag arises from two sources:

- Drag due to platform shape, C_D;
- Drag due to lift, C_D.

The first term is known as parasite drag and can be minimized by carefully shaping each aircraft part and minimizing intersections. The second term is made up of two components, inviscid drag due to lift and viscous drag due to lift. Because of the high Reynolds Numbers at which most modern aircraft operate, the viscous drag component has been a second order term and could be eliminated from standard industry drag estimation methods. The CO-OPS platform operates in a regime in which viscous drag due to lift may account for up to 10% of total drag and, therefore, must be

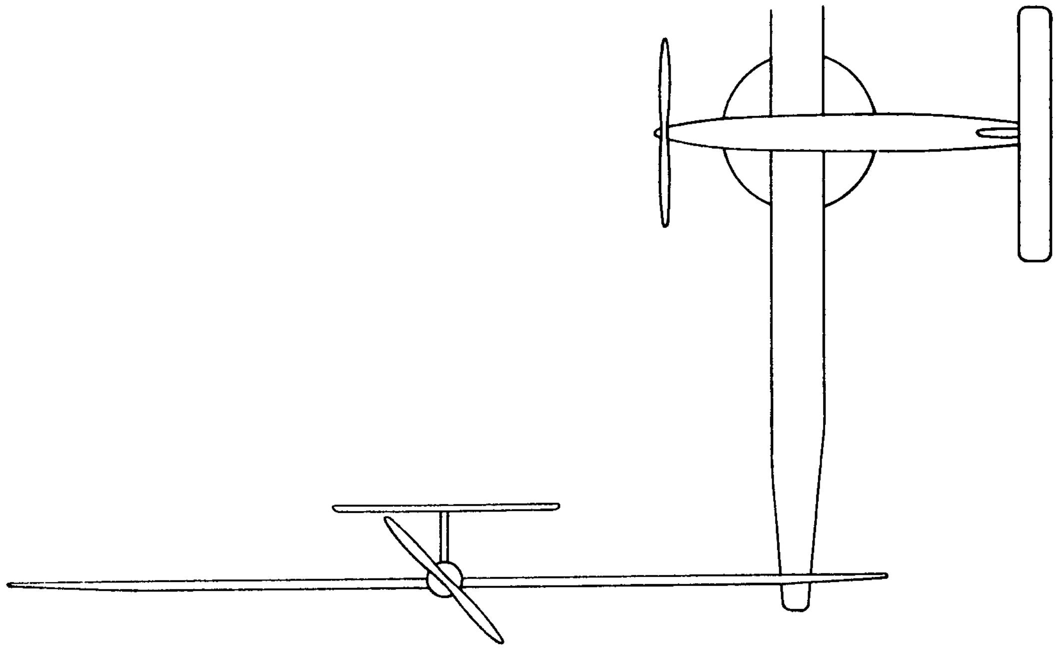


Figure 12. Typical Platform Configuration with Disk-Mounted Rectenna

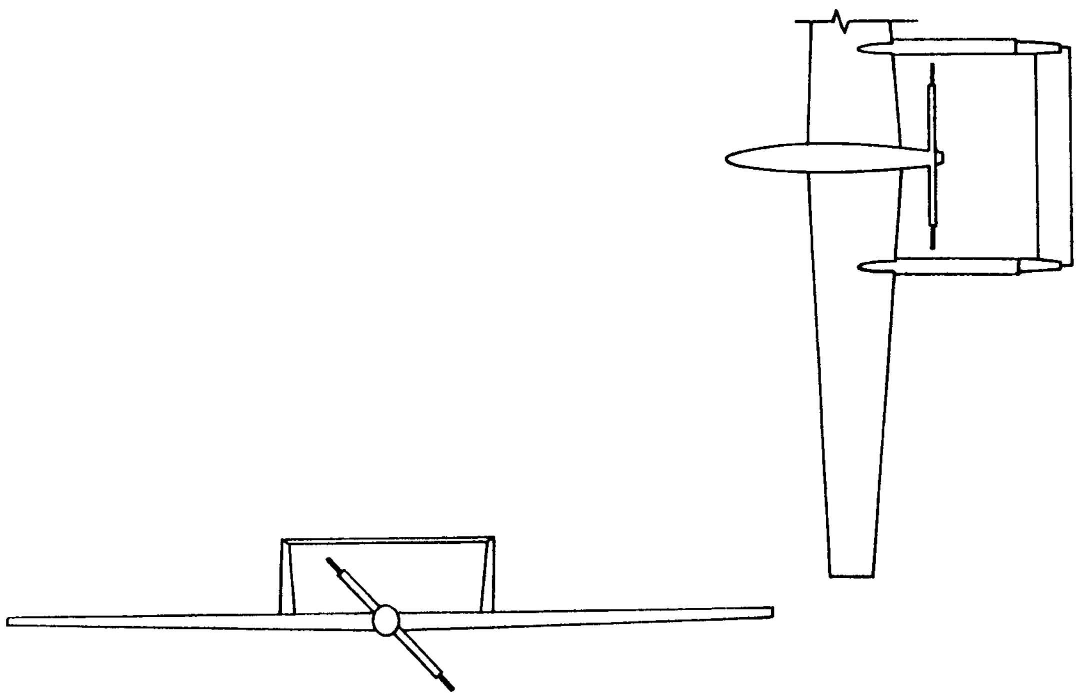


Figure 13. Typical Platform Configuration with Wing-Mounted Rectenna

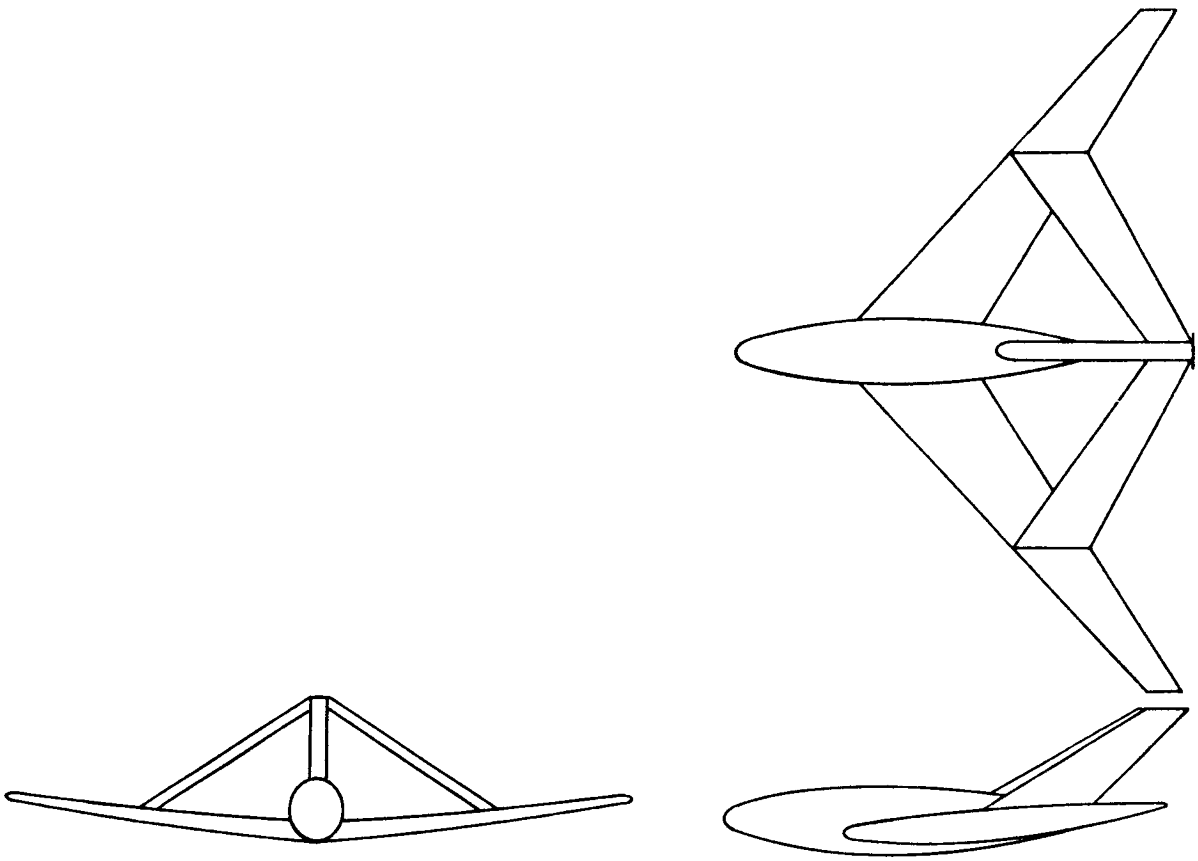


Figure 14. Typical Joined Wing Configuration With Wing-Mounted Rectenna

accounted for in calculations. The aircraft zero-lift drag prediction technique used in this methodology is a simplification of the DATCOM method developed by McDonnell-Douglas for the Air Force in the 1960's (Ref. 32).

The number of flying surfaces is set at three (wing, horizontal and vertical) and the number of bodies (fuselage, nacelles, pylons, booms) is set at one. Flying surface points of maximum thickness-to-chord ratio are initialized to be indicative of carefully tailored high lift, low Reynolds Number airfoils and a correction factor is added. The fuselage length is calculated here at seven mean geometric chords.

Two sets of aerodynamic parameters are then calculated. The first is skin friction coefficient followed by the zero-lift drag coefficients of each of the flying surfaces. The second set of parameters is the corresponding numbers for each of the bodies. After the zero-lift drag coefficient, C_D, is calculated, viscous drag due to lift is added to it. This viscous drag term, C_D, is a multiple of wing zero-lift drag to account for the non-parabolic drag polars typical of high lift low Reynolds Number airfoils. The correction factor is a linear average of the C=1.6 point of several high lift airfoils (examples are Wortmann's FX61 series and Liebeck's L1003M) used in previous studies.

Aircraft Efficiency Factor,e

The aircraft efficiency factor, or Oswald Factor, is estimated using a compendium of industry practices since no one standard method provided reasonable values for all the aspect ratios considered during this study. The method used is simplified from K. D. Wood's method(Ref. 31) which is presented in one of the appendices of his design text. Wing efficiency factor is calculated with corrections for both taper and aspect ratio then a fuselage shape correction is added. Once platform efficiency factor has been calculated, induced drag, C_D, may be calculated.

This methodology is one of only two shared with a previous NASA study (Ref. 12) and is described in greater detail there.

5.4 Structural Mass Estimation

The domain occupied by microwave platforms is between the flight regimes of solar high-altitude powered platforms and conventionally powered HALE RPVs. The structural mass estimation techniques used during this study are a combination of those developed for Ref.s 12 and 13 and for several conventionally powered high-altitude long endurance platform configuration studies done since 1980. The mass estimation method for the CO-OPS platform is a linear average of these two methods. During an iteration loop in the sizing methodology, structural mass is calculated using both methods and then the results are averaged linearly by wing loading. The averaging method is shown below.

(Massairframe)CO-OPS=((TOGM/Sref.)CO-OPS- (TOGM/Sref.)SPHAPP)*(
(Massairframe)AOP - (Massairframe)SPHAPP)/ ((TOGM/Sref.)AOP-
(TOGM/Sref.)SPHAPP) + (Massairframe)SPHAPP) (1)

The first mass estimation subroutine was developed under NASA funding for Langley's Solar HAPP program. Ref.s 12 and 13 fully document the methods and results of this contract work. Inputs are takeoff gross mass, wing area and wingspan and the output is airframe mass.

The methods employed are multiples of basic aircraft design parameters and are indicative of the curve-fitting done during contract work to provide maximum flexibility. The empirical weight estimation method used here was adjusted to closely approximate past published paper and hardware designs. The first step is to calculate the speed of sound at altitude and cruise mach number. Wing mass is then calculated as a function of wingspan, aspect ratio, thickness-to-chord ratio, airspeed, wing area, maneuvering load factor and takeoff gross mass. These same parameters and the configuration geometries calculated earlier are then used to calculate detail structural component masses.

5.5 Interfaces

Microwave and Platform

One of the major system cost drivers is the interaction of the diameter of the focused microwave power beam, or spot, relative to rectenna and platform geometries. At a nominal altitude of 20 km (65 600 feet), the microwave power spot varies from about 10 to 40 m (33 to 132 feet) in diameter. Power density, measured in watts per square meter, is the greatest at the center of this spot and decreases roughly logarithmically toward the edges. Useful power is usually considered to exist between the center and a radius established at the points where power has decreased to one-half the value at the center of the spot. This smaller circle is known as the half-power circle and should ideally correspond to the diameter of the platform's rectenna. If the rectenna is a disk, then its diameter is limited to this value. There is a corresponding ground antenna diameter to produce the required spot size for every ground power option.

There are a wide variety of platform subsystem shapes to carry the rectenna. These shapes may vary from a circular wing of just more than aspect ratio 1 and slightly larger than the half-power circle in diameter to a very efficient sailplane wing of very high aspect ratio. The highly efficient aerodynamic shape will require less power than a less efficient shape but will intercept less of a circular spot. Because less is intercepted by a highly efficient sailplane type wing, more power must be beamed up and more must be generated on the ground requiring a larger array. The tradeoff to be performed, then, is between highly efficient subsystems aloft and on the ground and less efficient subsystems optimized to work together to minimize total system cost. Platform subsystem configuration and ground subsystem options change the details of this trade, but not the basic logic.

Very high aspect ratio wings (above 25) result in very high microwave power losses because the slender wings intercept such a very small percentage of the power in the "power circle", while very low aspect ratio wings (below 6) have very high power required (high drag), therefore these extreme configurations were ruled out very early in the analyses.

Payload and Platform

Payload factors affecting system ability to take continuous in-situ measurements for long durations are payload mass, drag producing payload attachment features such as viewing ports or fairings, and odd viewing angles for calibration. Features which create drag result from the need for instrument ports in the platform skin or bulges to hide unsightly lumps and corners. Viewing ports are required to ensure that the platform provides those interfaces required to achieve the second mission goal of observation. Required viewing ports will depend on the particular observation. NADIR viewing instruments and scanners looking through NADIR will require a clear view of earth. Limb viewing instruments will require a clear view of the earth's limb. Some limb scanners must observe the sun as it rises and sets and, hence, may determine platform flightpath during part of each day's mission. Solar viewing instruments must be able to continuously track the sun. Most instruments will frequently need to be calibrated by viewing either the sun and/or deep space. Platform structure must be excluded from the viewing envelope in all cases.

To summarize, viewing requirements will be:

- Placement of payload instruments on the platform in accordance with the viewing requirements of each payload instrument;

- Careful coordination between the payload observation timeline and the operational timeline flightplan of the platform.

Payload viewing requirements may dictate modifications to the instruments, although such modifications could be costly and should be kept to a minimum.

To successfully make the required observations, payload contamination must be rigorously controlled. The necessity for contamination control will place requirements on the design and operation of the platform. Special protection of the payload will be required during all phases of the mission including preflight, climb to altitude, daily operations and during descent and recovery.

Instruments having components at cryogenic temperatures will require special attention to preclude icing up. Certain infrared instruments require cooled detectors to achieve low-noise measurements. Passive cooling using a radiative cooler is typical and the cooler is designed to couple the detector to cold deep space. The efficacy of a radiative cooler operating in the stratosphere requires further study. It may not be able to achieve sufficiently low temperatures due to earthshine scattering off the residual atmosphere at altitude, emission from the residual atmosphere and contamination buildup from both the atmosphere and the platform. In addition, warm windows would be required over the detector and over the radiative cooler inner stage to prevent contamination buildup. At a minimum, the detector window will require refocus of the payload optics system. The window may require further redesign of the instrument and may adversely affect radiometric performance. The radiative cooler inner stage window, if needed, may adversely affect the ability of the cooler to radiatively cool the detectors. Hence, other means may be necessary. Alternatives might be passive stored cryogen or an active refrigeration system.

Since the platform is bathed in microwave radiation, the instruments must operate in this environment. This may require shielding of instruments and cables.

5.6 Life Cycle Cost Model for the Platform

The life cycle cost model used for the platform is derived from a method published in Ref. 25. As with other analytical and parametric models used during this study, the original costing method was not directly applicable to high-altitude long endurance aircraft. Some basic assumptions were made and specific cost factors were added to bring estimates into line with industry experience. The Ref. 25 method used requires the following inputs:

- Airframe mass (AMPR) in kilograms;
- Wing area (AREA) in square meters;
- Cruise airspeed (VCRUISE) in meters per second;
- Number of platforms to be produced monthly (ACPM) and during the entire program (QQ);
- Engineering cost per hour in 1984 dollars (ECH);
- Tooling cost per hour in 1984 dollars (TCH);
- Labor cost per hour in 1984 dollars (LCH);
- Rectenna cost per square meter in 1984 dollars (RCM);and
- Propulsion subsystem cost including gearbox and propeller in 1984 dollars (MC).

The methodology will then yield a platform cost for RDT&E. Several of the required inputs listed above are initialized at values typical of technology demonstration programs such as CO-OPS. These are:

- Number of platforms to be produced monthly (ACPM) = 1 and total production run (QQ) = 10;

- Engineering cost (ECH) = $75.<</hour;
- Tooling cost (TCH) = $56.<</hour;
- Labor cost (LCH) = $44.<</hour;
- Rectenna cost (RCM) = $2150./sq m; and
- Propulsion subsystem cost (MC) = $75,000.<<.

The engineering cost equation is labeled COST1 and is calculated as:

EE = .0396*AMPR .791*VMAX 1.526*QQ .183 (2)

where AMPR is platform airframe mass. (3)

COST1 = EE*ECH

Development support cost is labeled COST2 and is found as follows:

COST2 = .008325*AMPR .873*(1.3*VCRUISE) 1.89*2 .346 (4)

COST2 = COST2*3.5 (5)

Cost of flight test operations is estimated as COST3 and is:

COST3 = .001244*AMPR 1.16 *VMAX 1.371*2 1.281 (6)

COST3 = COST3*3.5 (7)

Tooling cost is labeled COST4 and is defined as:

TT = 4.0127*AMPR .764*(1.3*VCRUISE) .899*QQ .178*ACPM .066 (8)

COST4 = TT*TCH (9)

Manufacturing labor cost is labeled COST5 and is defined as:

LL = 28.984*AMPR .74*(1.3*VCRUISE) .543*QQ .524 (10)

COST5 = LL*LCH (11)

Quality control cost is labeled COST6 and is:

QC = .13*LL (12)

COST6 = QC*LCH (13)

Manufacturing material and equipment cost is labeled COST7:

COST7 = 25.672*AMPR .689*VMAX .624*QQ .792 (14)

COST7 = COST7*3.5 (15)

Rectenna cost is labeled as COST8 and is defined as:

COST8 = EAREA*RCM (16)

Electric motor cost is COST9:

COST9 = MC (17)

Total cost per aircraft is ACCOST and is defined as:

ACCOST = COST1 + COST2 + COST3 + COST4 + COST5 + COST6 + COST7 + COST8 + COST9 (18)

5.7 Results

Operational Characteristics

The control mode anticipated for both let-down and landing and take-off and climb-out operations is one where the platform is remotely controlled by a combination of ground-based pilot and airborne pilot in a chase plane. The pilot on the ground will be provided with flight director type displays which contain not only status information but predictive displays and maneuver limit boundary indications. The predictive displays show dynamically what the platform attitude will be if the pilot's controls are held at current values. A second situation display will show the aircraft's flight path relative to the runway for the landing maneuver. Heavy reliance on flight simulation is anticipated to set the boundaries on acceptable stability and control characteristics, stability augmentation requirements, control powers and rates, and the nature and characteristics of the pilot's displays.

Orbiting at cruise altitude is the second major flight segment of interest in establishing flight control requirements. Tracking of the aircraft's position relative to the center of the microwave beam will be accomplished by a ground based system. Depending upon the beam power gradient, however, it may be feasible to include a simple onboard backup system which could be used. A general figure-eight flight path will be biased, depending upon winds, to keep the platform within the beam. This function will be accomplished by an autopilot/guidance system.

If an up/down link is assured, a novel design approach may be taken. In this approach the onboard attitude, rate or other required sensor signals are transmitted to the ground where the guidance, autopilot and stability augmentation computers are located. The surface command signals, in turn, are then transmitted to the platform. The advantages of this approach are that the computer may be kept in an ideal environment, backup computers may be provided, and this onboard mass is removed from the platform.

Assuming that the signal gradient backup position scheme mentioned above is feasible, a simplified backup autopilot/guidance system could be provided onboard for short-term operation if the up/down link is temporarily lost. Regardless of the degree of integrity required of the up/down link, this link will be used to provide a manual override capability from the ground-based piloting station to either sustain orbiting operations for some period or to initiate controlled recovery operations for some period.

Physical Size Characteristics

Several platform subsystems appear viable for use in a CO-OP System. Presented in Table 20 are ten platforms with indications of size, mass, cost and development readiness. Cruise airspeed used is 50 meters per second (97 knots) at altitudes from 19 to 21 km (62 to 70 kfeet) and payload mass is 270 kg (595 lbf).

In Table 20, the letters A through E refer to ground subsystem options as follows:

A SLOTTED ARRAY ON PEDESTALS WITH MAGNETRONS

B SLOTTED ARRAY WITH MAGNETRONS

C 4.5M DISH WITH MAGNETRONS

D 11M DISH WITH KLYSTRONS

E SLOTTED ARRAY WITH solid-state

In addition to these platform subsystems which were sized for moderately high-altitude operation, a platform was sized for operation at an altitude of 37km (121 kfeet). This platform would have a wingspan of 110m (361 feet) with a total first system RDT&E cost of between $200M and $300M in 1984 dollars.

TABLE 20. VIABLE PLATFORM SUBSYSTEM OPTIONS

RECTENNA	GROSS MASS	WING-SPAN	ASPECT RATIO	FLUX DENSITY REQUIRED	COST (1984$M)	DEVELOPMENT READINESS
WING WITH D	698KG	34M	14	510W/SQM	7.29	
WING WITH C	683KG	36M	16	490W/SQM	7.30	
DISK WITH D	755KG	40M	19	494W/SQM	7.94	
WING WITH A	785KG	40M	14	424W/SQM	8.16	SEE NOTE
DISK WITH B	778KG	44M	21	405W/SQM	8.32	
WING WITH E	807KG	40M	13	406W/SQM	8.33	
WING WITH B	821KG	42M	14	405W/SQM	8.54	
DISK WITH C	842KG	48M	21	411W/SQM	8.98	
DISK WITH E	858KG	50M	22	401W/SQM	9.23	
DISK WITH A	872KG	50M	22	419W/SQM	9.32	

NOTE: All platforms utilize state-of-the-art technology and manufacturing, therefore the development readiness of all ten configurations is considered excellent.

6.0 GROUND POWER AND PROPULSION SYSYSTEMS

6.1 Overview

Although the emphasis during this study was on microwave power, a wide variety of propulsion options was considered. Table 21 summarizes the various propulsion classes and lists advantages and disadvantages for each.

TABLE 21. ALTERNATIVE POWER TRAINS

TYPE	ADVANTAGES	DISADVANTAGES
Reciprocating Engines	Low Fuel Consumption Low Power-to-Weight Ratio	Heavy Power Train (if fuel, tanks and plumbing are considered) for long missions. Endurance limited to a to 2 weeks even with careful design
Turbines	High Power-to-Weight High Reliability	Heavy power train for long missions Higher fuel consumption than reciprocating engines. Endurance limited to one week or less even with careful design.
Radio-Isotropic Generators	Endurances of six months to several years theoretically possible	Very heavy power trains for any mission Very expensive Fuels unavailable in sufficient quantities Radiation danger Political constraints on use
Solar Thermal and Solar Photovoltaic	Adequate space technology base for further development Infinite endurances theoretically possible at some latitude	Heavy power trains Small payload capability even for very large aircraft
Microwave	Adequate technology base for immediate development	Large ground-based power generation system required even for small aircraft

Each propulsion subsystem above will be cost-effective for a specific set of endurances. Figure 15 below is a simplified representation of the endurances where each propulsion subsystem is viable. As can be seen from the preceding table and from Figure 15, only regenerative power systems will meet a long mission duration requirement such as is necessary for CO-OPS durations on the order of two months (700 hours). The systems described below are turbojet (TJ), turbofan (TF), turboprop(TP), reciprocating (Recip) and regenerative (Regen). Two items are of interest in the plot below: The y-intercept of each line is the tare mass of the power train which includes fuel tanks and fuel management systems as well as the propulsor. The slope of each line is determined by the fuel consumption of each type of propulsor.

The three regenerative power train options were discussed in the Introduction to this report. Radio-isotopic generators require further development for airborne applications and face significant political problems before being used over some of the populated areas mentioned in the CO-OPS mission requirements section. Solar power, while applicable to low latitude missions, is not suitable for high latitude missions such as those above 60^{o} north latitude or over the arctic or antarctic ice sheets. It is for these reasons that this study has focused on microwave power trains.

6.2 Atmospheric Environment

Characterization of Winds aloft Over Mission Sites

The environment in which CO-OPS will operate during its primary mission will be relatively benign. Thorough studies have been made of the meteorological micro-climate over the prototype verification test site and other sites proposed for operations and these data are summarized below. (Ref. NASA report, "Study of Winds aloft for the Development of Design Criteria for Unmanned SKHILO aircraft", by Stanley I. Adelfang, Contract NAS8-34010, Sept. 86.)

The biggest concern to CO-OPS is winds aloft which can markedly complicate station-keeping with the platform. As can be seen in Figure 16, a summary of worst case winds for six mission sites, expected winds aloft exceed the design speed of 50 mps (97 kts) at 20 km (65,600 feet) far less than 1 percent of the time. Statistically, for a two-month mission, this would be less than 15 hours.

The two curves above are summaries of worst case (99th percentile) winds aloft for six sites which will be discussed next. Presented next are plots of the 50th, 95th and 99th percentile wind speeds in meters per second at six locations which are listed below. These percentiles represent the mean, two and three standard deviation points, respectively, on normal distributions of data.

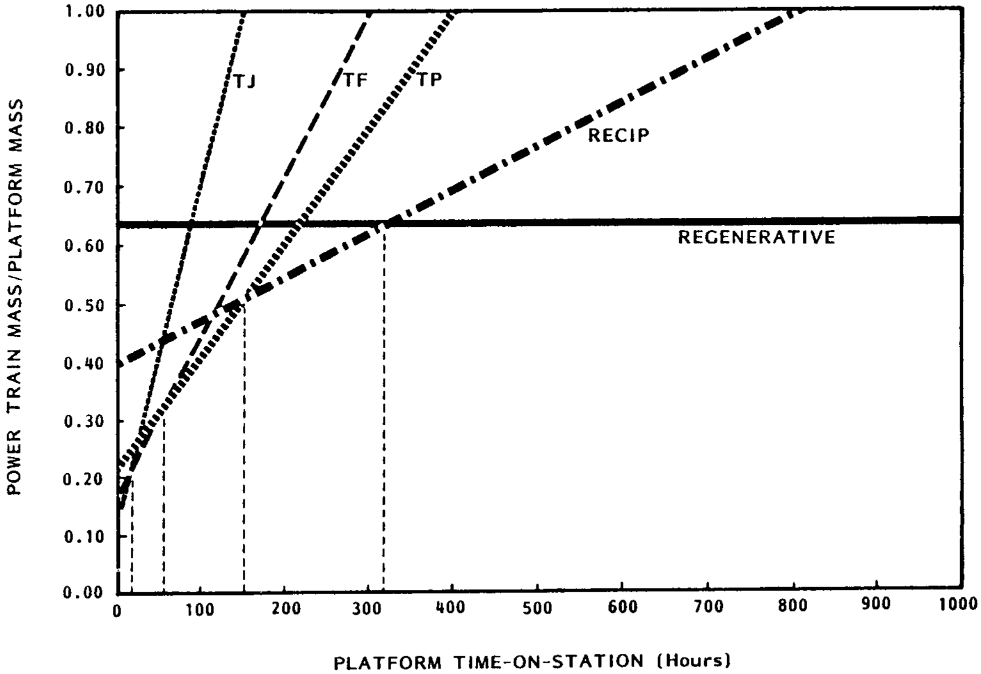


Figure 15. Comparison of Power Train Options for a CO-OPS Mission

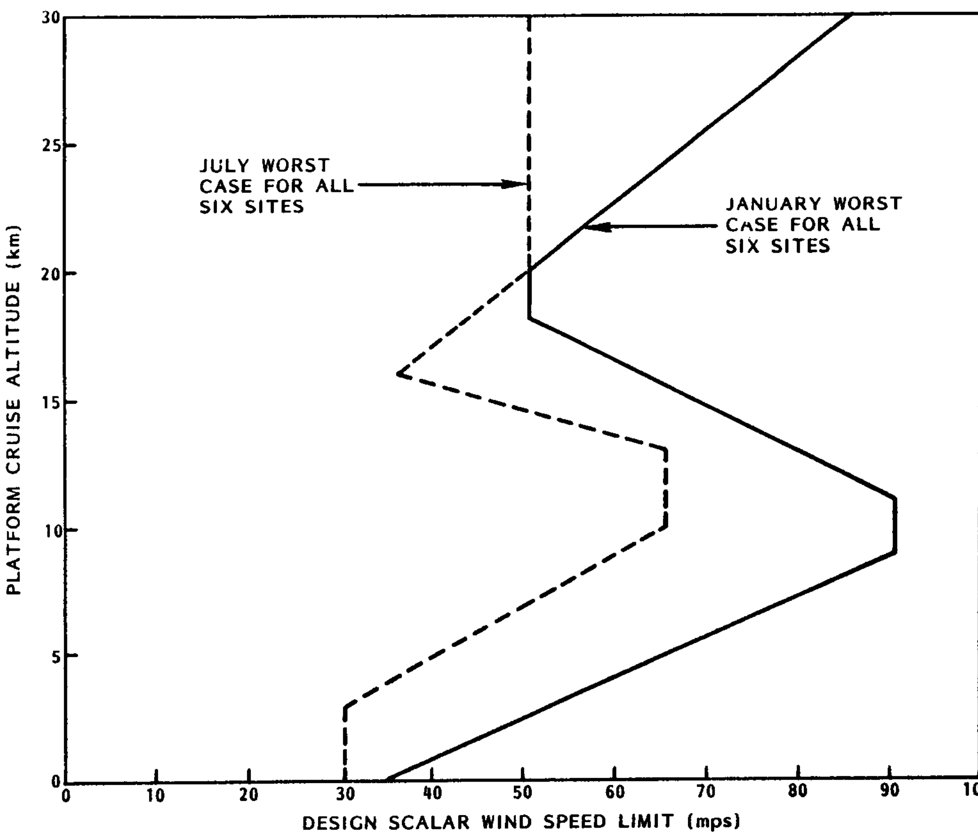


Figure 16. Platform Design Cruise Airspeed Lower Limit Based On Worst Case Winds Aloft for Six Sites

Location	Site Number
Nashville, Tennessee	1
Vandenberg AFB, California	2
New York City, New York	3
McMurdo Sound, Antarctica	4a
San Andreas Island, Colombia	4b
Frobisher Bay, Northwest Territory, Canada	5

The percentiles for four of the locations are given for January and July to represent seasonal variations. For Frobisher Bay and McMurdo Sound, it was necessary to group the data in the winter season to obtain a larger data sample. The December/January/February grouping for Frobisher Bay yields a sufficient amount of data for calculation of the three percentiles at all altitudes (1 to 27 km (3.3 to 88.6 kfeet)). The June/July/August grouping for McMurdo Sound permitted calculation of the 95th percentile to 25 km (82.0 kfeet) and the 99th percentile to 22 km (72.2 kfeet). In every case presented in Figures 17 through 23 below, the left curve represents 50th percentile data, the middle curve represents 95th percentile data and the right curve represents 99th percentile data. Sites are presented to correspond to the numbering above Figures 23A and B are summaries of the 99th percentile winds for each site grouped by month of year. Even though one set of southern hemisphere data is presented in each grouping, its placement in a winter-summer grouping would not change the resulting design wind curves derived here.

The final set of plots given in Figures 23 includes heavy lines to the right of 99th percentile wind data. These lines are the platform design true airspeeds which were used in this study. The value at each point on the heavy lines is approximately 10% greater than the highest measured wind speed value in order to provide design margin during parametric sizing calculations.

Note that in many cases the platform design true airspeed is much higher than required to overcome winds aloft at specific sites. This difference may be dealt with in several ways. It may be reduced by reducing airspeed to approximately 10% more than the maximum wind speed value at the site in question. To recall the discussion of Figure 5, this will result in larger wing areas and higher values of wing lift coefficient. The larger wing areas will result in larger, more expensive aircraft but the increase in platform cost may not offset the decrease in the size and cost of the ground subsystem. Increases in wing lift coefficient will provide an upper bound to decreases in airspeed.

A large margin between airspeed and maximum expected wind speed may be ignored. The resulting margin in power available may then be used to provide more flexibility in maneuvering the platform. This would also provide more mission flexibility for the CO-OP System, allowing one system design to be used over all required sites.

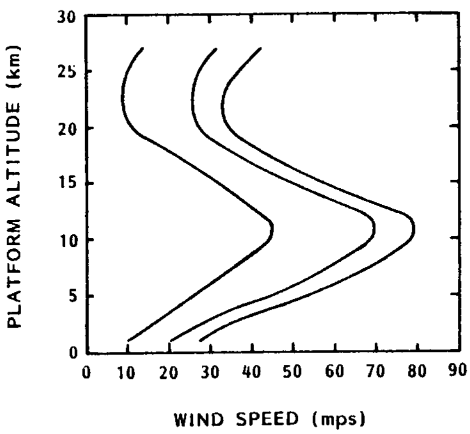


Figure 17A. January Scalar Winds Aloft Over Nashville, Tennessee

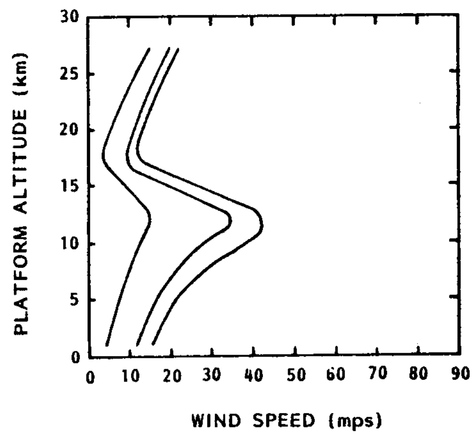


Figure 17B. July Scalar Winds Aloft Over Nashville, Tennessee

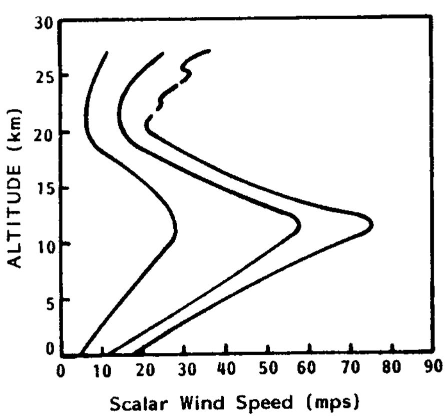


Figure 18A. January Scalar Winds Aloft Over Vandenberg AFB, CA

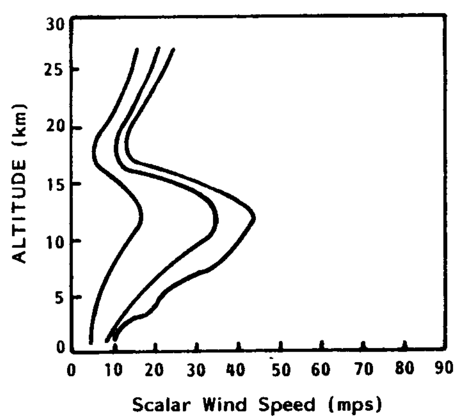


Figure 18B. July Scalar Winds Aloft Over Vandenberg AFB, CA

Lockheed

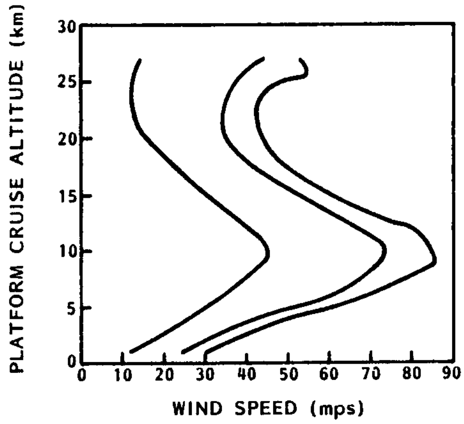


Figure 19A. January Scalar Winds Over New York City, NY

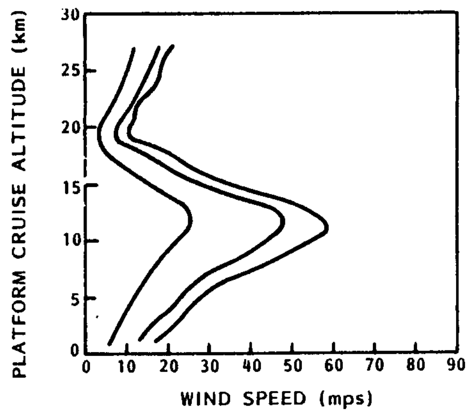


Figure 19B. July Scalar Winds Aloft Over New York City, NY

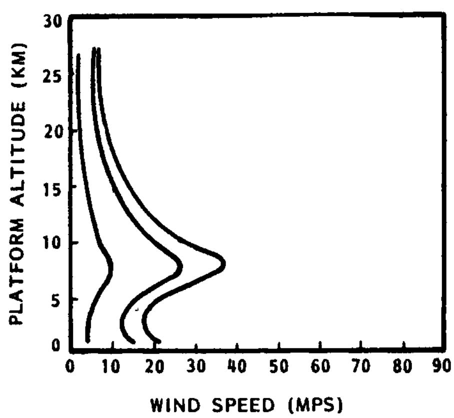


Figure 20A. January Scalar Winds Aloft Over McMurdo Sound, Antarctica

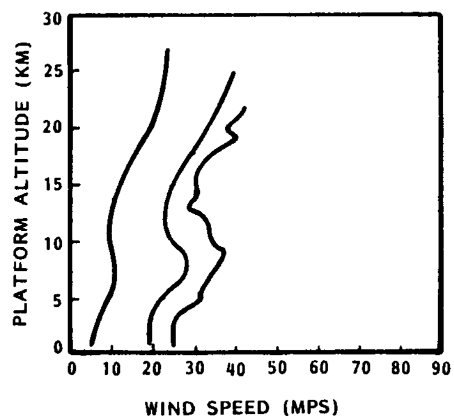


Figure 20B. July Scalar Winds Aloft Over McMurdo Sound, Antarctica

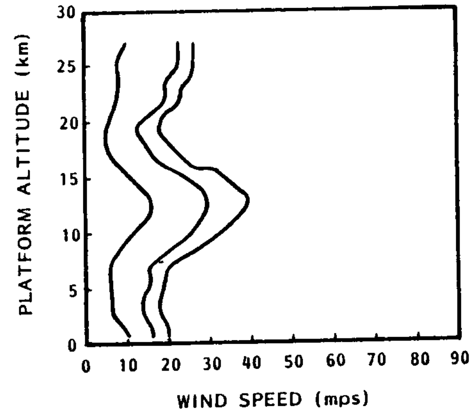


Figure 21A. January Scalar Winds Aloft Over San Andreas Island, Columbia

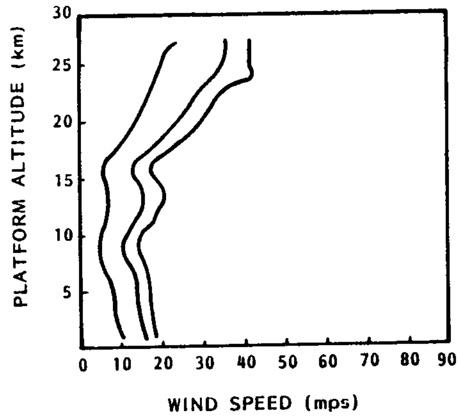


Figure 21B. July Scalar Winds Aloft Over San Andreas Island, Columbia

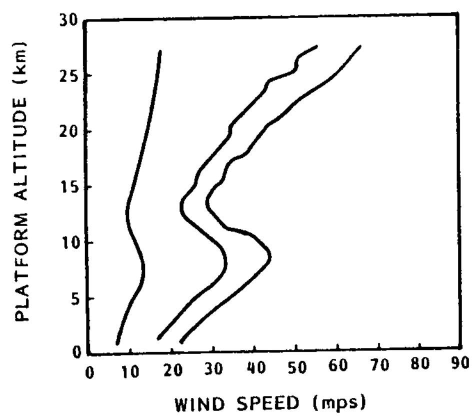


Figure 22A. January Scalar Winds Aloft Over Frobisher Bay, Northwest Territory, Canada

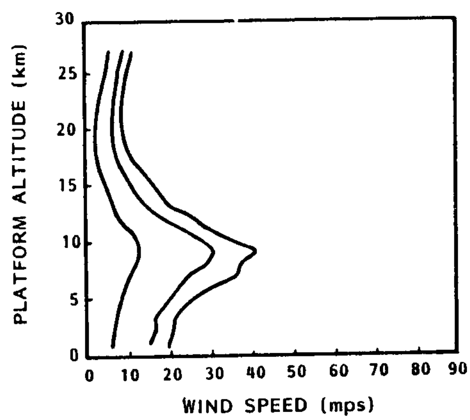


Figure 22B. July Scalar Winds Over Frobisher Bay, Northwest Territory, Canada

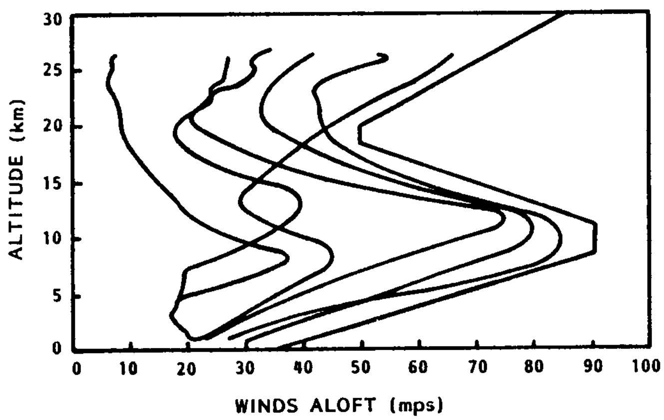


Figure 23A. Summary Worst Case January Scalar Winds Aloft for all Six Sites

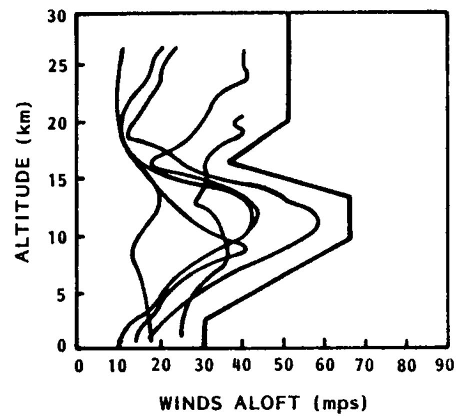


Figure 23B. Summary Worst Case July Scalar Winds Aloft for all Six Sites

A large margin between airspeed and maximum expected wind speed might also be dealt with by removing some ground subsystem modules at sites where winds aloft are not close to design airspeed values. This would again allow one system design to be used at all six sites, but would reduce operating cost of the ground subsystem by requiring less power. Airspeed could be reduced to some value which was lower than the maximum required for operation at every site but higher than a value which would require redesign of the platform.

Not considered in this study were the following meteorological factors:

- o Ground meteorological problems at mission sites;
- o Airborne temperatures at mission sites;
- o Airborne humidity levels at mission sites;
- o Clouds; and
- o Unusual atmospheric phenomena at mission sites.

These should be dealt with in future studies before serious system design begins.

6.3 Ground Power Subsystem Characterization

Overview

Using microwaves as a means of transmitting energy through free space to power an airborne vehicle was first demonstrated in the early 1960's with a DC-to-DC efficiency of 13%. In 1975, a DC-to-DC efficiency of 54% was achieved and, with advances in component technology, DC-to-DC efficiencies of 70% or more may be expected. Coupled with the advances in component technology has been the maturing technology of phased array antennas. These developments have now made a remotely powered aircraft feasible.

The overall CO-OPS system block diagram is depicted in Figure 24. All blocks within the dashed box are part of the ground power sub-system. The ground power sub-system contains all of the elements required for transmitting microwave energy in a collimated beam to the aircraft and provides a communication link with payload sensors on the aircraft. The control link serves two functions in the ground power sub-system. First, the control link supplies positional data to the ground array so that the ground array main beam can track the aircraft in flight. Secondly, it supplies power level data enabling the ground array to adjust the power received at the rectenna. The RF power level must be maintained at a level high enough for prime power on the aircraft, but not so high as to damage the solid-state components in the rectenna. The communication link can provide the same data as the control link, but is primarily intended as a data link for the payload sensors.

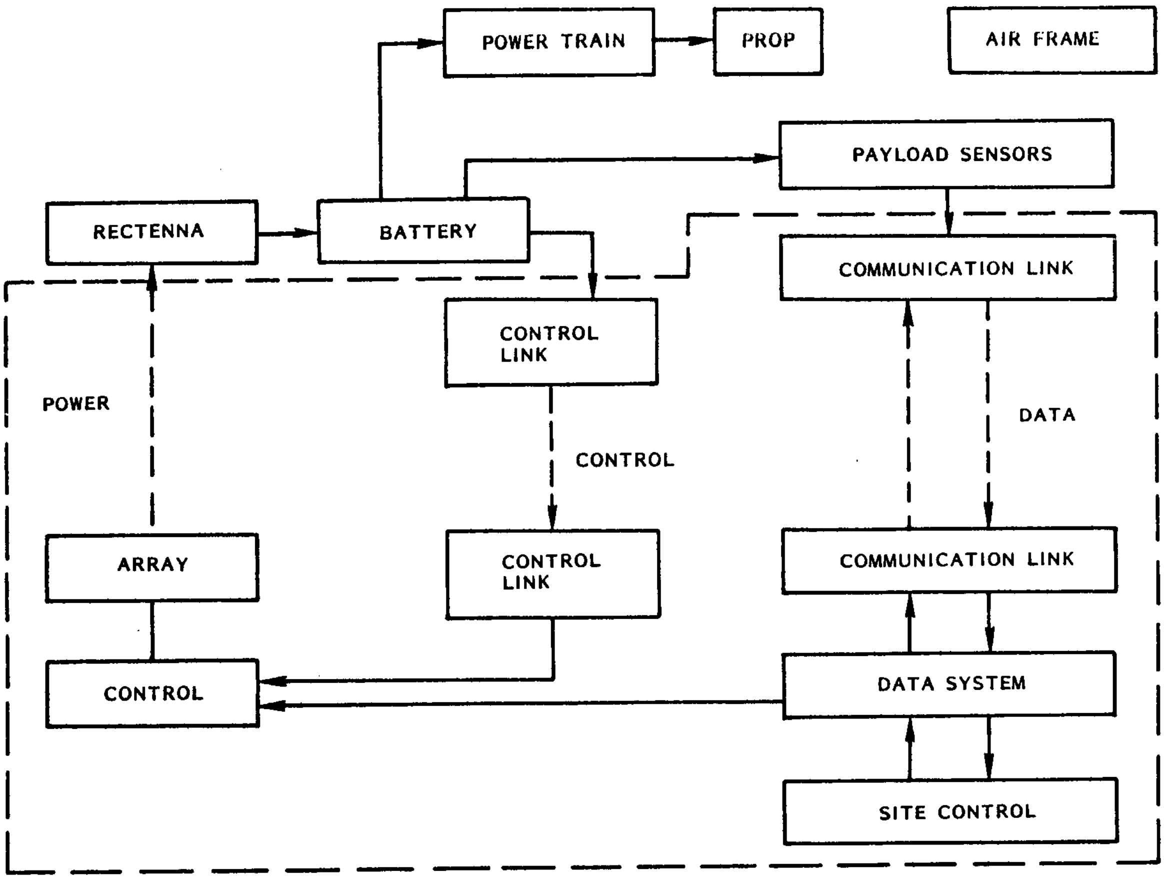


Figure 24. Simplified System Block Diagram

A more detailed block diagram of ground power sub-system appears in Figure 25. A coherent RF reference source is necessary to provide phase coherent signals to the radiating elements of the phased array. Relative phasing of the array's elements is the method by which the main beam of the array is steered and focused. The reference signal is distributed, via coaxial cables or waveguide, to the array elements where the low power coherent signal is either used to phase lock the high power RF signal in the case of a magnetron oscillator, or simply to amplify the coherent source signal to a higher power level in the case of tube or solid-stated type amplifiers.

Microwave power from the transmitter is input directly to each array element or can be subdivided to feed a number of array elements. A cost trade-off study shows that it is more costly to subdivide the transmitter power to a sub-array.

The size of the antenna required to produce the necessary beamwidth for the CO-OPS (up to 25,000 square meters) makes it impractical to implement this antenna concept by any means other than a phased array antenna approach. This array could take on many forms based on the approach taken to implement the sub-array. For example, the sub-array could be a stationary slotted array; it could be a parabolic dish antenna mounted on a pedestal or it could even be a slotted array section mounted on a pedestal. All approaches have been implemented and all may be considered "off the shelf".

Mechanically scanned antennas would only be used with parabolic dish or pedestal mounted flat plate sub-arrays. The purpose of mechanically scanned, pedestal mounted antennas is to point each of the sub-array beams at the aircraft rectenna thus eliminating scanning losses. The focusing of the array main beam will still require a phase shifter in each of the transmitters.

The preferred location of the phaseshifter is at the input to the transmitter. At this point, the power handling requirement of the phase shifter is at a minimum and so is the cost.

All of the elements shown in Figure 25 contribute to the cost. The major cost drivers, however, as will be shown later, are the ground power transmitters and the antenna arrays. Other elements, such as the RF reference source, require a microwave signal distribution system in which additional low powered amplifiers may be necessary. Although it is not a cost driver by itself, this distribution system can easily increase the transmitter cost by 5 to 20% depending on the transmitter ultimately selected. All components must be considered in the cost model to ensure a correct trade-off analysis between various transmitter and array candidates that could be applicable to the CO-OPS program.

Antenna Approaches

A number of candidate antenna technologies have been considered. These are tabulated in Table 22 along with the three important CO-OPS

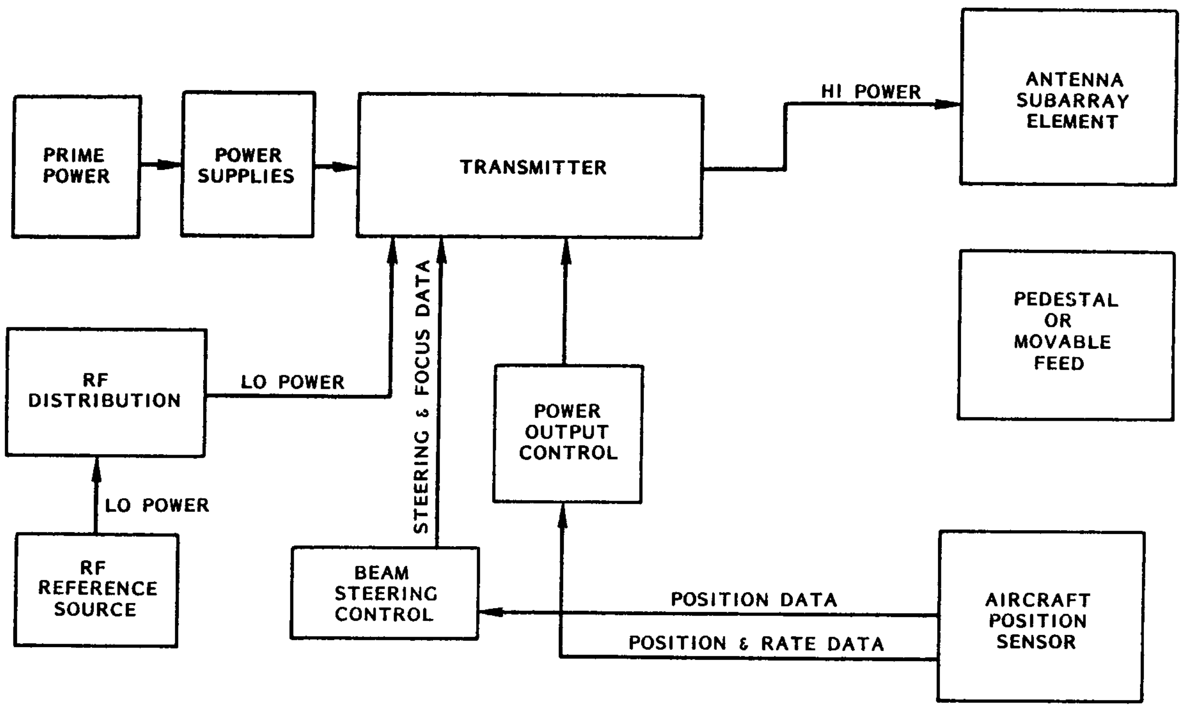


Figure 25. Ground System

TABLE 22. ANTENNA APPROACHES

ANTENNA	MTBF (HRS)	COST RANGE	RISK	SCAN RANGE
SLOTTED ARRAY	30000	\$800 - 900/SQM	LOW	±12°
DISH/	20000	\$1.6K-2.6K/SQM (4.5M DISH)	LOW	0.45°
PEDESTAL		\$1.7K-1.9K/SQM (11M DISH)	LOW	
DISH/ FEED SCAN	20000	\$1.7K-1.9K/SQM (11M DISH)	LOW	±10°
FLAT PLATE/ PEDESTAL	20000	\$1-1.3K/SQM	LOW	±45°

considerations MTBF, cost and risk. The slotted array shown in Figure 26, has no moving parts, but does need to have hot air to melt ice and a liquid spray to clean its surface, hence the 30,000 hr MTBF. The dish/pedestal and the flat plate (slotted array) on a pedestal both use an azimuth, elevation pedestals that are capable of 360° Azimuth and 45° from vertical scan coverage. The dish feed scan system uses feed motion to scan the beam. A suitable technique for this candidate is the Cassagrain antenna.

Dish/Pedestal

The dish/pedestal requires a two axis clover azimuth mount to achieve the plus or minus 45° elevation and 360° coverage. For large antennas (i.e., 11M), the mount is quite sizeable and requires a concrete base. Regardless of its size, the antenna can be made portable. It can be disassembled, packed, and reassembled at a new site. Costs were based on data received from two firms, Scientific Atlanta and Andrew Corporation.

In addition to large scan coverage, this antenna also has the advantage of being able to dump water and snow. It, however, requires a large heater of up to 10 KW to prevent ice build up.

Dish/Feed Scan

This system relies on movement of its feed system to steer the type feed system. The scan may be accomplished by moving the low inertia feed or subreflector. The motor required for this would be approximately 0.5 HP as opposed to a 30 HP motor required for the dish/pedestal system, although additional losses would be incurred at the edge of the scan region.

Flat Plate/Pedestal

The flat plate is actually a group of slotted array subarrays. It has the same large scan coverage advantage as the Dish/Pedestal, but at a lesser cost. This cost reduction is the result of using a slotted array transmitter with a reduced cost feed system rather than a rotary joint dish feed system. The cost of this system is slightly greater than the fixed slotted array. Its large scan coverage eases the aircraft control problem by permitting the aircraft to fly farther down range. Wind gusts that cause large deviations in course are also of less concern. In contrast to the dish/pedestal which also has these same characteristics, the flat plate array has a high efficiency because of the elimination of three losses: the blockage, the taper and rotary joint. A total improvement in efficiency of approximately 1.5:1 can be expected.

Transmitter Approaches

The key elements in the transmitter affecting the cost is the transmitter tube or power output device selected for the CO-OPS program. A search was made of the currently available S-band and C-band transmitter

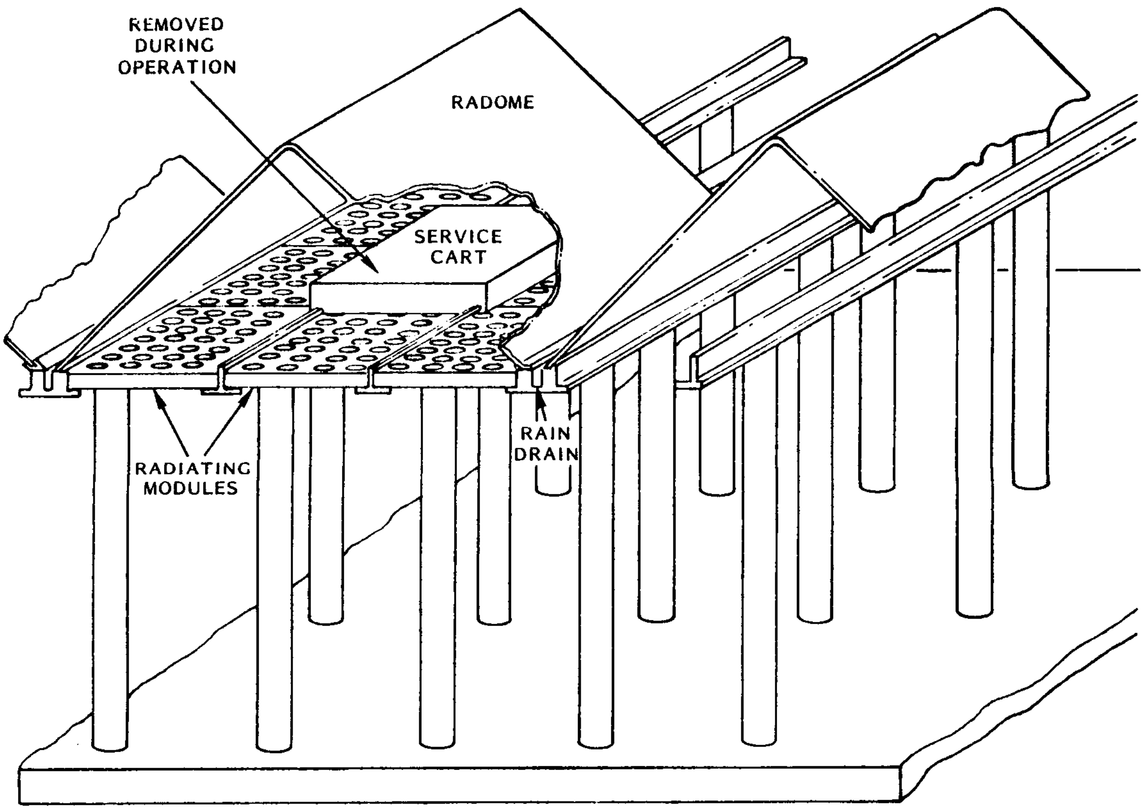


Figure 26. Slotted Array Configuration

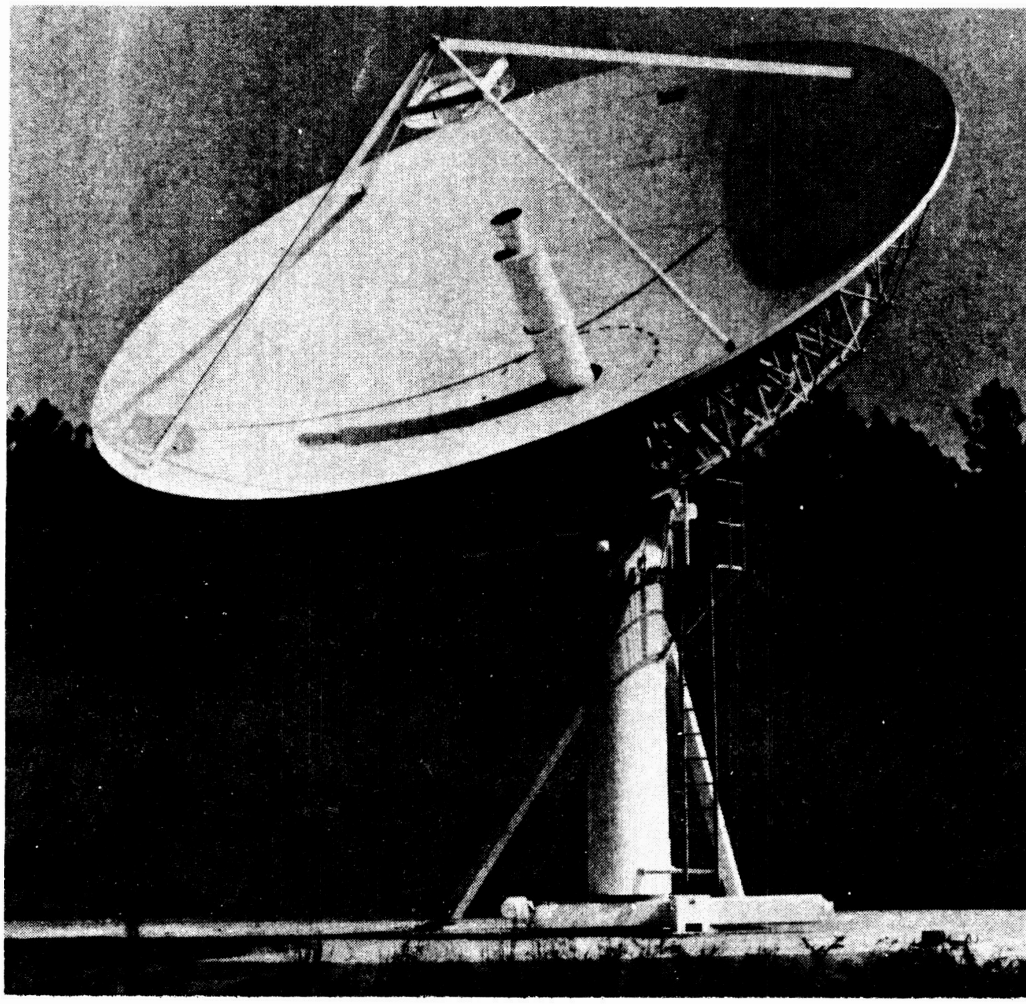


Figure 27. 11-Meter Disk Antenna

tubes and devices that might be used. Table 23 shows a summary of the representative tubes and solid-state amplifiers.

With the exception of the solid-state device, all tubes are in or have been in production. The solid-state amplifier has been produced in small quantities to demonstrate its producability but, tooling and facilities are required to produce sufficient quantities to be cost competitive with the tube amplifiers and the magnetrons. Thus, it has been assessed a moderate risk as shown in Table 23.

Power output varies widely between these transmitter approaches. All power outputs are nominal and allow for at least a 20% upward adjustment. By doing so, a margin is provided for modulating the power to meet the varying needs of the aircraft propulsion power when flying in wind. To increase power beyond the 20-30% range requires paralleling tubes.

Air cooling is preferred over liquid cooling since it greatly simplifies the transmitter design and improves maintenance.

Efficiencies of all the transmitter types are the same and all can meet the requirement of high efficiency.

The MTBFs given are estimates based on experience with transmitters of each type. The two magnetron systems considered are the microwave oven and an industrial heating tube. Both have a higher MTBF simply because in each case more money was expended to produce an extremely reliable device. The key in both cases has been in the cathode/heater design evaluation.

Costs vary widely between the various approaches. The least expensive is the 500W cooker magnetron transmitter. A primary reason for this is its large production. This tube is currently being produced by the Japanese for under $20.00.

The most expensive approach, in terms of dollars per watt, is the solid-state device. Compensating for the cost disadvantage to some extent is its higher reliability. The degree to which reliability compensates depends on the array size and design. The 500W magnetron is more applicable to larger subarrays. The lower power solid-state is applicable to smaller subarrays; this partially compensates for the lower power of the solid-state. For example, the cooker magnetron might be coupled to a 16 element slotted subarray while the solid-state amplifier might be used in a 4 element subarray.

Of the various approaches, the cooker magnetron is the cheapest from the standpoint of production cost. It is, however, an injection-locked amplifier as opposed to a linear amplifier. The design of the injection-locked amplifier is not as straightforward as that of the linear amplifier as can be observed in comparing Figures 28 and 29. In addition, there are the following concerns:

TABLE 23. COMPARISON OF TRANSMITTER APPROACHES

TRANSMITTER	POWER OUTPUT	COOLING	MTBE	COST	RISK
S BAND					
MAGNETRON	500W	AIR	20kHr	$1.8/W	LOW
MAGNETRON	5kW	LIQ	10kHr	$3.9/W	LOW
KLYSTRON	30kW	LIQ	6kHr	$5.3/W	LOW
SOLID STATE	10W	AIR	100kHr	$36/W	MOD
C BAND					
KLYSTRON	10-20kW	LIQ	6kHr	$3-5/W	LOW
KLYSTRON	3.4kW	AIR	6kHr	$32/W	LOW
TWT	12kW	LIQ	6kHr	$7-10/W	LOW

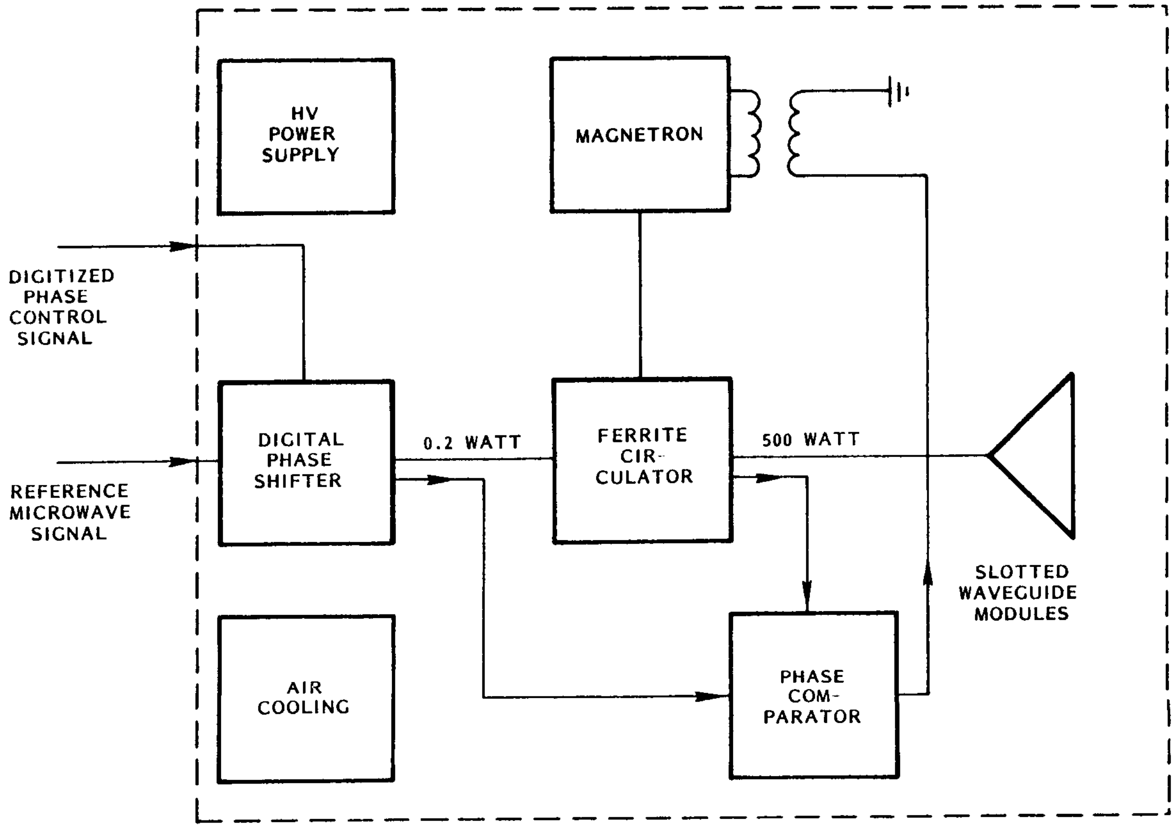


Figure 28. Ground Transmitter Magnetron Candidate

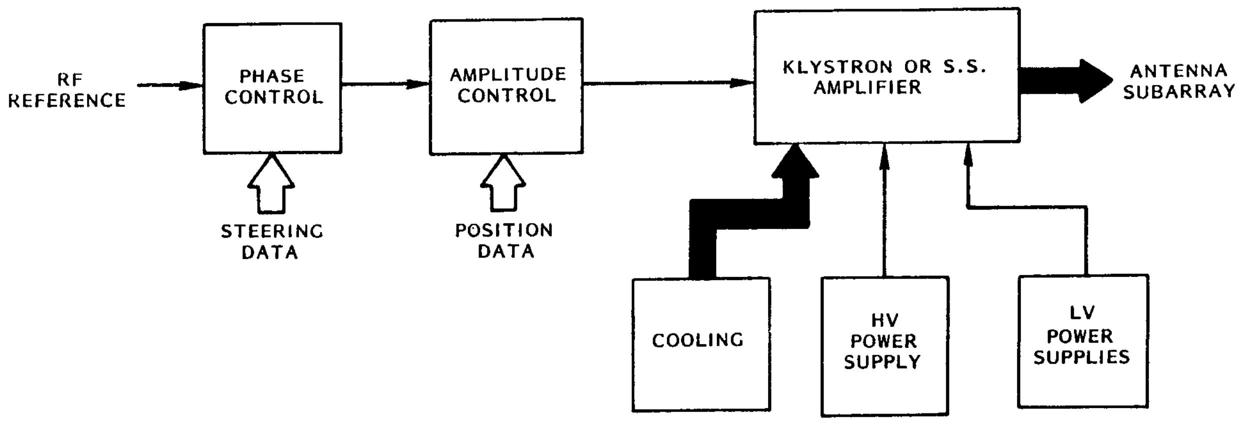


Figure 29. Ground Transmitter AMplifier Candidate

a) Out-of-band noise and harmonics (a concern for all high powered microwave devices).
b) Coherency

Since it is a likely candidate because of its price advantage, a more detailed discussion follows.

Phase Locked Magnetron Operation

The magnetron directional amplifier itself consists of the magnetron and either a three port or a four port ferrite circulator. Consider first that the phase lock is removed and that the magnetron is running freely as an oscillator with no signal applied to the drive port of the circulator. It will oscillate at a frequency determined by its own internal resonant frequency and a Reflector power component which appears to the magnetron as a complex impedance. The imaginary part of the impedance appears to the magnetron as a reactance which will change the magnetron's operating frequency.

The magnetron, however, cannot distinguish between power that is injected from an external source and that which is reflected from the output load. The competitive effect of the reflected power can be eliminated with the use of a directional device which diverts the reflected power into another port of the circulator. This leaves the input power from driver to interact with the magnetron. This input power from the driver will lock the frequency of the magnetron and change the phase of its output power. The phase of the output is related to the phase of the input, the external Q of the magnetron, and the ratio of the power output level to the drive level by the following expression:

$$\sin {}^{o} = Q_e(f_1-f_2)/fo\ (P_1/P_o) \qquad (1)$$

Where Q_e is the external Q of the magnestron, f_1 is the injected frequency, f_2 is the free running frequency of the magnetron when drive power is not injected, P_i is the power level of the injected signal, P_o is the power output of the magnetron, and f_o is the nominal operating frequency of the magnetron, in this example 2.45 GHz.

Expression (1) indicates that the phase shift between input and output can be held to zero if the free running frequency of the oscillator coincides with that of the drive signal. If zero phase shift between input and output or "phase lock" is desired then some method of automatically tuning the magnetron to operate at the drive frequency and some method of comparing the phases of the input and output to control the amount and direction of tuning is required.

A phase detector in the form of a double balanced mixer compares the output phase of the amplifier with the input phase. Any difference in the output phase generates an error signal that varies the amount of current flowing in the "buckboost" coil which alters the magnetic field applied to the magnetron. The modified magnetic field varies the anode potential which, in turn, electronically tunes the magnetron's output frequency. The feedback loop keeps changing the frequency of the magnetron until it comes very close to that of the drive signal and the error is reduced to near zero.

The relationship between frequency and current in the magnetron is shown in Figure 30. Over 15 MHz of tuning is obtained by varying the current between 100 and 300 milliamperes in this experimental data taken under conditions in which no heater power is applied to the filament. Even more frequency shifting can be obtained by operating the tube with some filament current to allow operation at lower values of anode current. It is noted that the power output from the magnetron varies over a power range of 200 to 1000 watts with the efficiency remaining fairly constant but increasing to 70% at the high power end. Such power output and efficiency are typical of the magnetron when operated without heater power which is a desired condition. However, it can be operated quite satisfactorily at lower power levels with some heater power applied to the filament.

The behavior of the magnetron directional amplifier may now be understood when the phase locking feature is added and the driver frequency is changed. This relationship is shown in Figure 31. This is the same experimental relationship between phase shift and driver frequency change shown in Figure 32. In addition, the variation of power output with frequency change is noted. This experimental data was taken with some heater power applied to enable operation at lower output power levels.

In the phased array it is desirable to control the illumination pattern over the face of the array. Uniform illumination is the simplest and provides the most efficient coupling to the aircraft. In this case, all of the individual radiation modules should radiate the same amount of power. This would require that all of the magnetron directional amplifiers should output the same power at the same drive frequency which means in turn that the free running frequency of the magnetrons should be the same at the same power output level.

To obtain a measure of the variations between tubes, a sample lot of Hitachi 2M107A magnetrons was obtained and power output versus frequency plotted for the members of the sample. This data is shown in Figure 33. At a given frequency it is observed that there is a considerable variation in power output, but that the slopes of the curves, with one exception, are similar. Therefore, it would be possible to have the curves (with the one exception) to fall on each other if there were some form of trimming that could be externally applied to the tube. In actual practice it is possible to even use the tube with the different slope if all the tubes were lined up at the most probable operating power point.

Lockheed

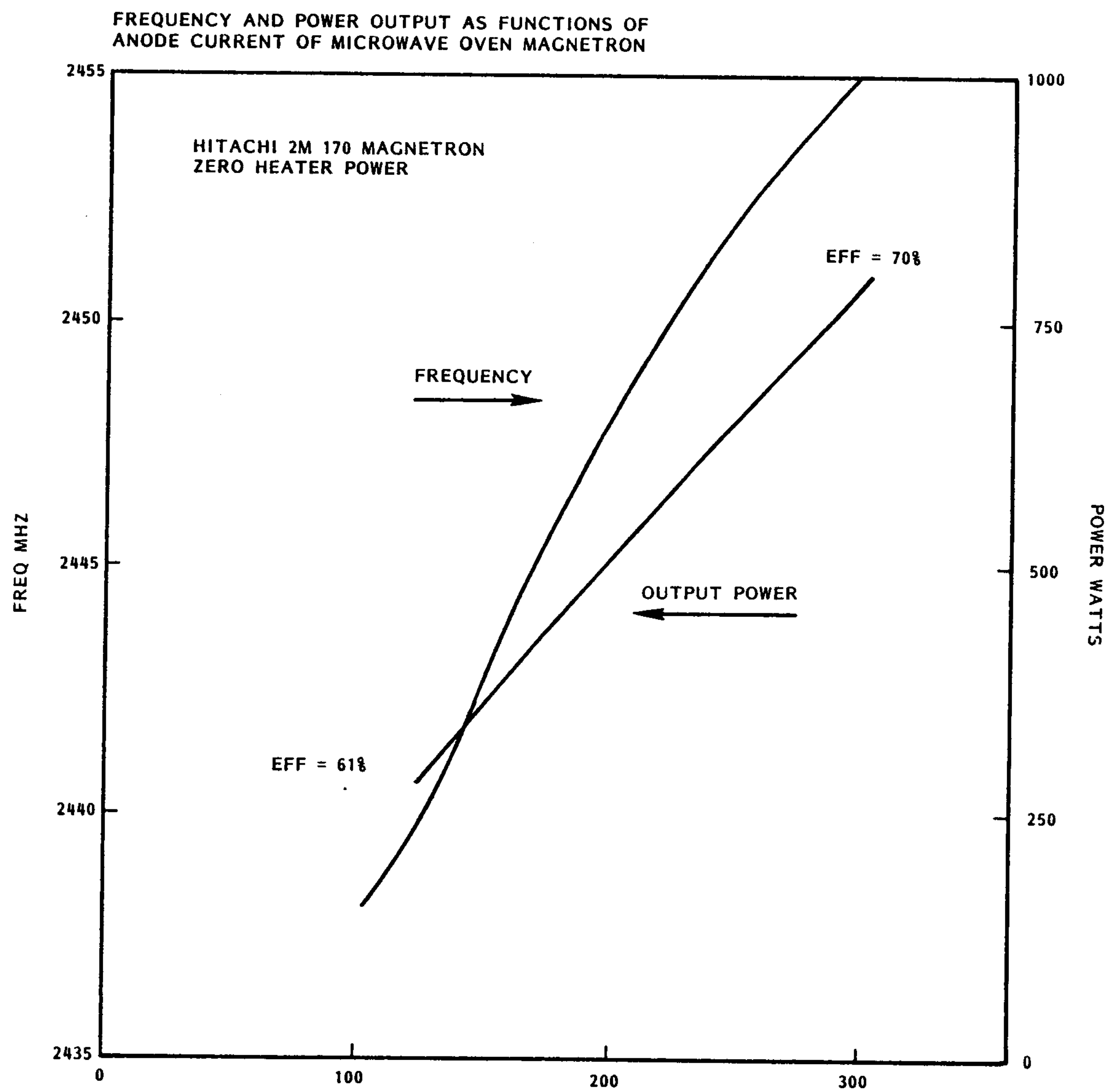
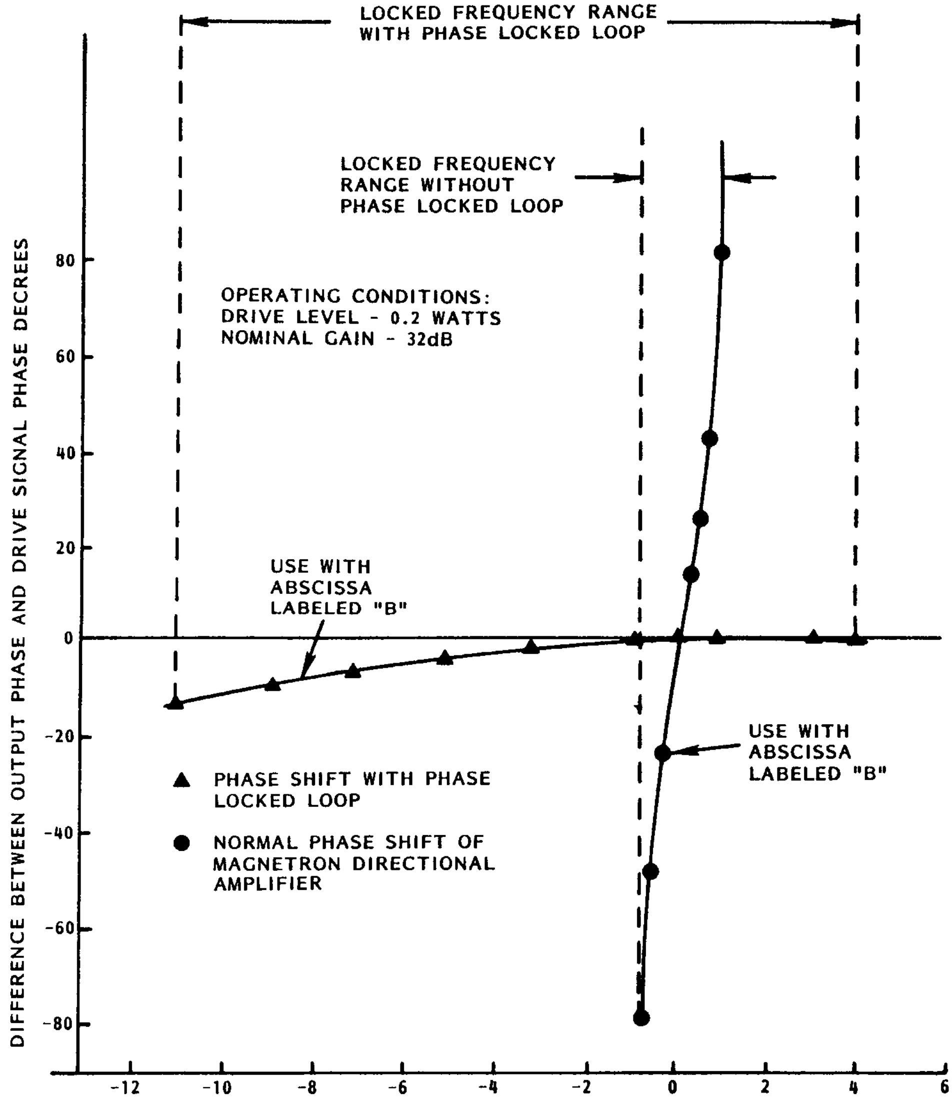


Figure 30. Magnetron Anode Current - Milliamperes



A. DIFFERENCE BETWEEN FREQUENCY OF DRIVE AND FREE RUNNING FREQUENCY OF MAGNETRON FOR THE CONVENTIONAL FREQUENCY LOCKED MAGNETRON DIRECTIONAL AMPLIFIER

B. CHANGE IN DRIVE FREQUENCY FOR PHASE LOCKED MAGNETRON DIRECTIONAL AMPLIFIER IN WHICH MAGNETRON FREE RUNNING FREQUENCY IS TUNED TO THE FREQUENCY OF THE DRIVER

Figure 31. Frequency Change - Megahertz

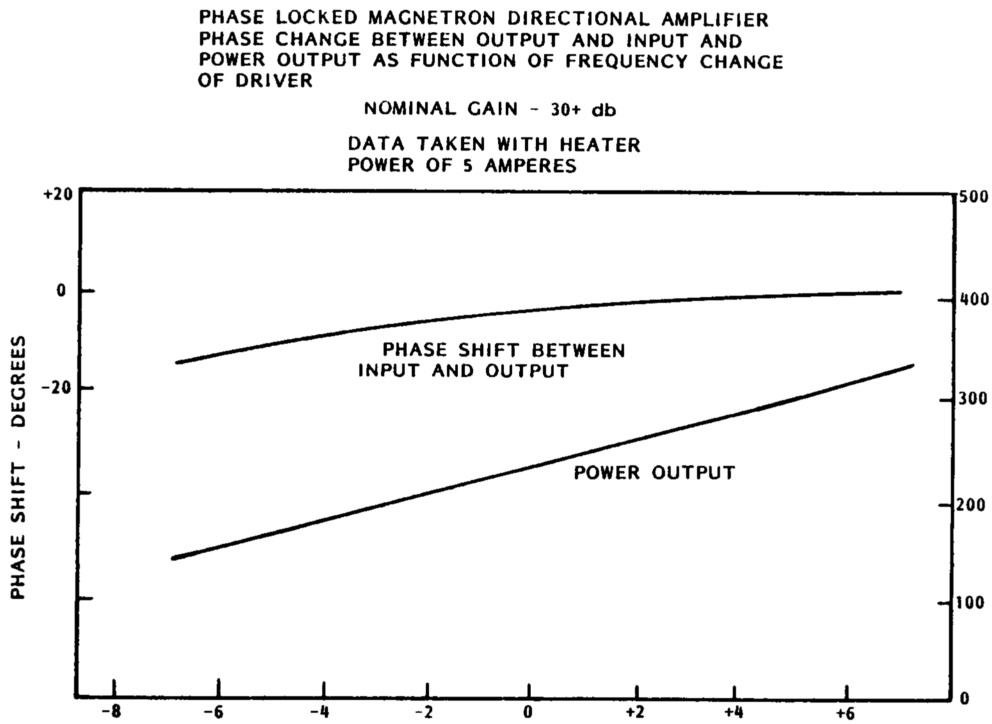


Figure 32. Driver Frequency Change - MHZ

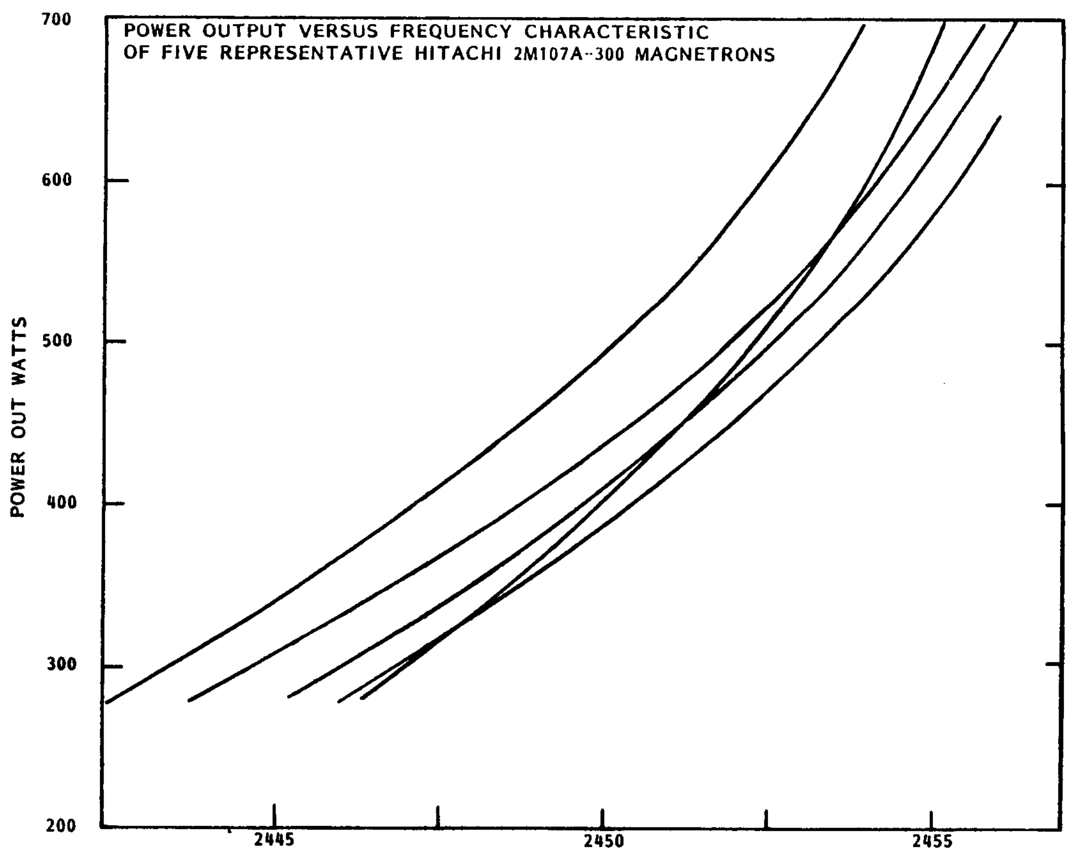


Figure 33. Oscillating Frequency - MHZ

Fortunately, the trimming can be easily accomplished by a simple threaded capacitance post placed at the proper spot in the waveguide into which the magnetron is inserted. This arrangement is shown in Figure 34, where the post is seen at the center. The relationship between the frequency of the magnetron and the turns of the tuner is shown in Figure 35. Power output is also plotted in the Figure. Tuning the magnetron is shown to have only a small impact upon the power output and efficiency.

The frequency trimming procedure just discussed obviously raises the question of how much frequency variation there is within a large sample of magnetrons. Routine data for lots of 2M107A magnetrons was obtained from Hitachi. The distribution curve of operating frequency at the test value of anode current is shown in Figure 36. This data indicates that the method of manufacture and the degree of control of the product assures very uniform operating frequency and is well within the usefulness of the trimming procedure just outlined.

Finally, the power distribution within a sample was also obtained and is shown in Figure 37. The associated operating efficiencies were closely grouped around 70.5%.

Noise Behavior

An extensive amount of data on the noise performance of the magnetron directional amplifier was taken under two NASA contracts related to the Solar Power Satellite Investigation and these were supplemented by a Raytheon Independent Research project. The magnetron directional amplifier exhibited noise levels that were low enough such that the only driver device quiet enough not to add to the noise level of the magnetron was another magnetron.

Extensive experimental data was taken on the noise properties of the magnetron directional amplifier and reported upon in the final NASA reports. Figure 38 shows the kind of low noise performance obtained from the magnetron directional amplifier over a wide range of current and voltage. Although some noise begins to appear at higher voltages when additional magnetic field is added, the noise is very low in the voltage regime where the microwave oven magnetron is operated, typically 3.5 to 4.0 kilovolts.

The low noises level is relatively independent of the gain in the magnetron directional amplifier. With 0.6 watts of drive power the gain is 30 dB. However, at this gain level, the locking frequency range is very narrow and the phase shift change with frequency is very rapid. When phases lock is added the low noise level is still maintained but the phase shift between input and output remains close to zero over a very wide frequency range.

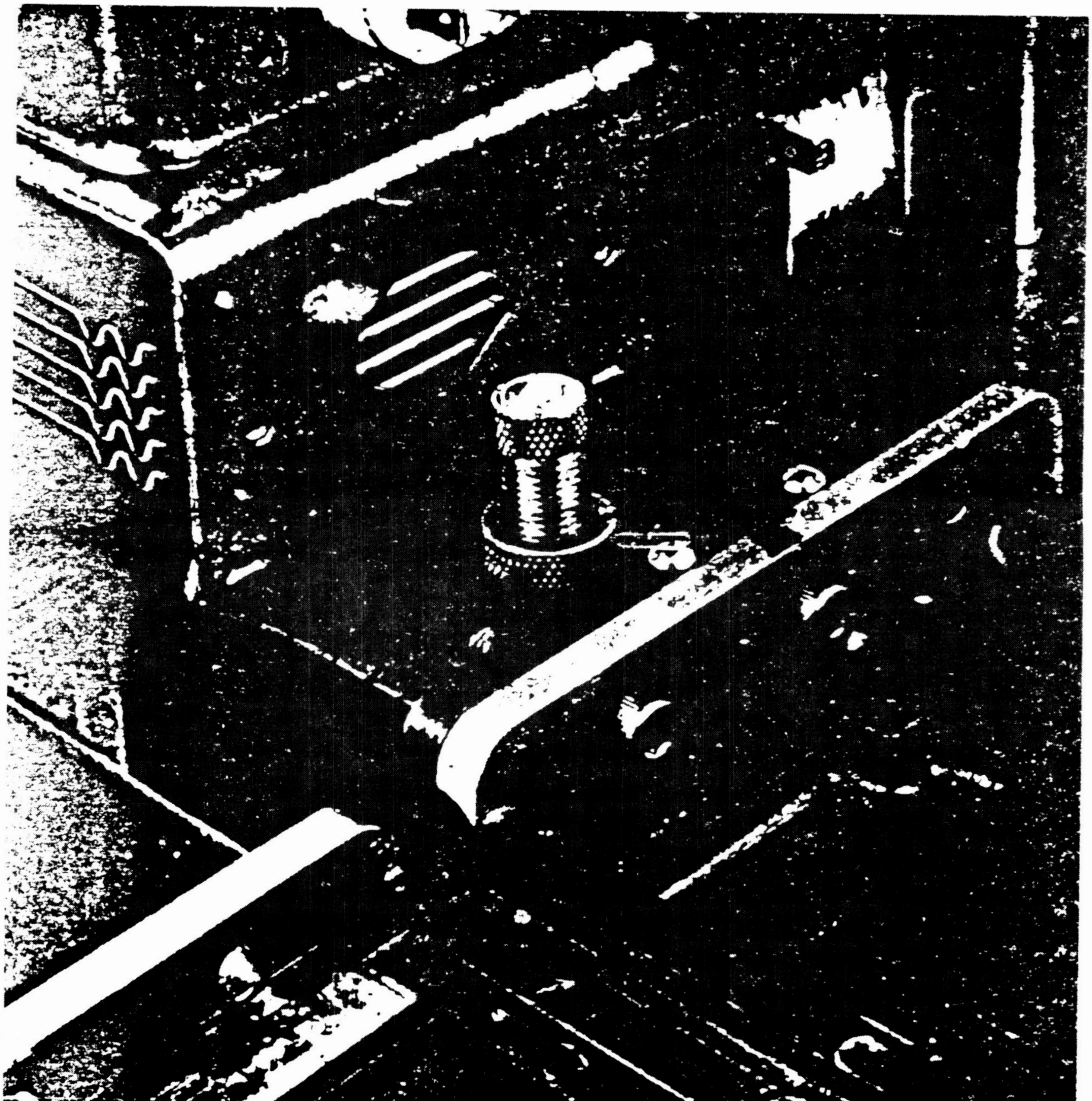


Figure 34. Magnetron Trimming

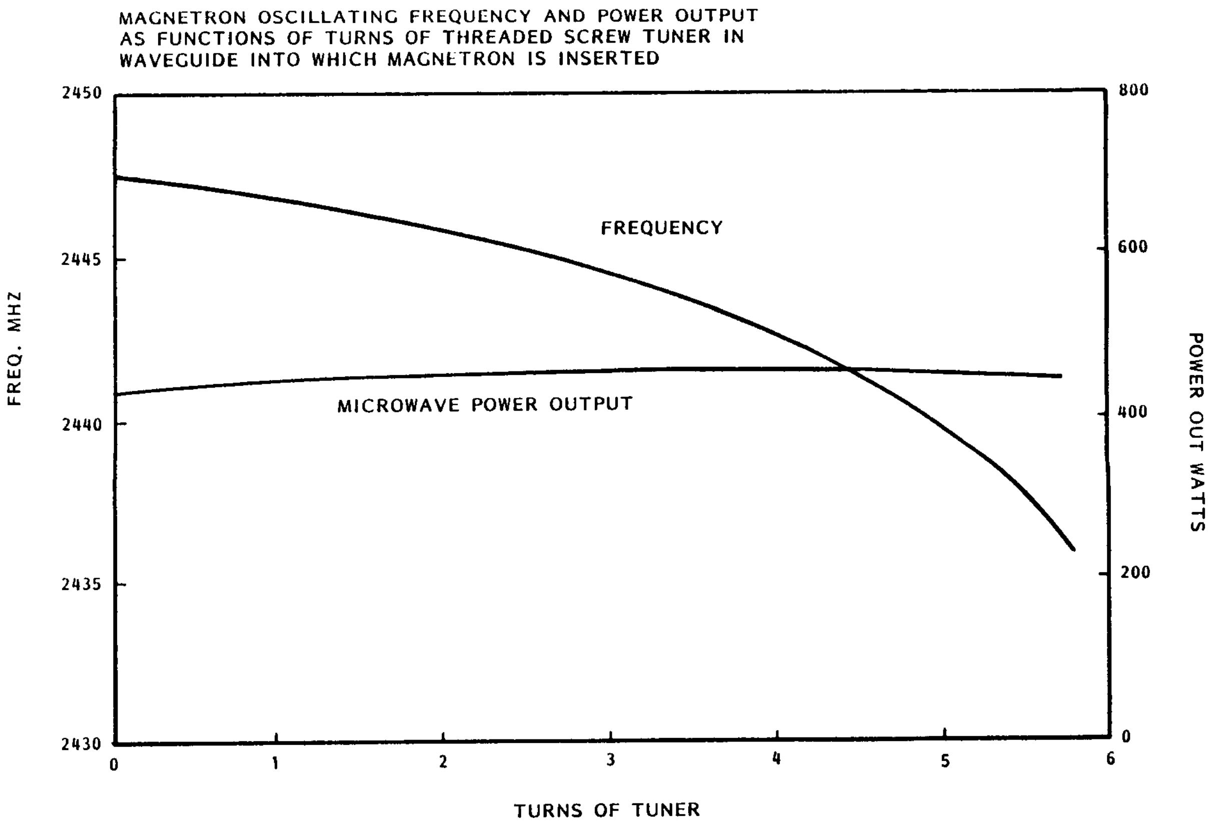


Figure 35. Frequency Vs. Power Output

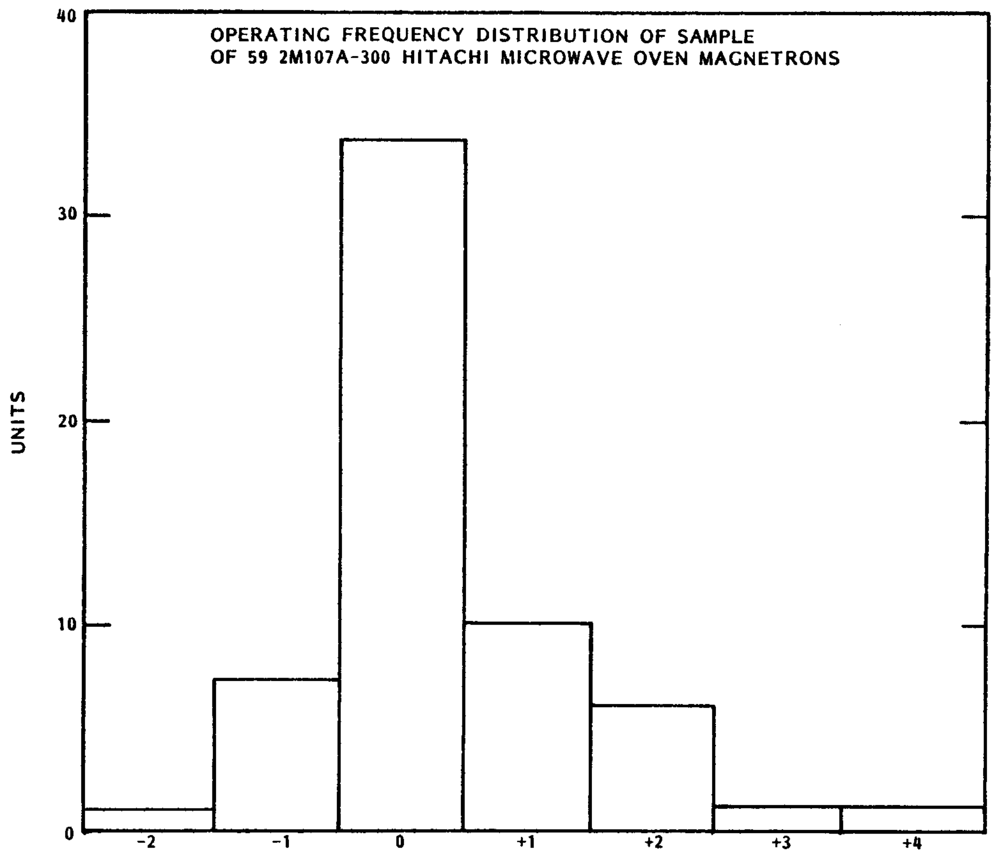


Figure 36. Frequency Change from Sample Mean Megahertz

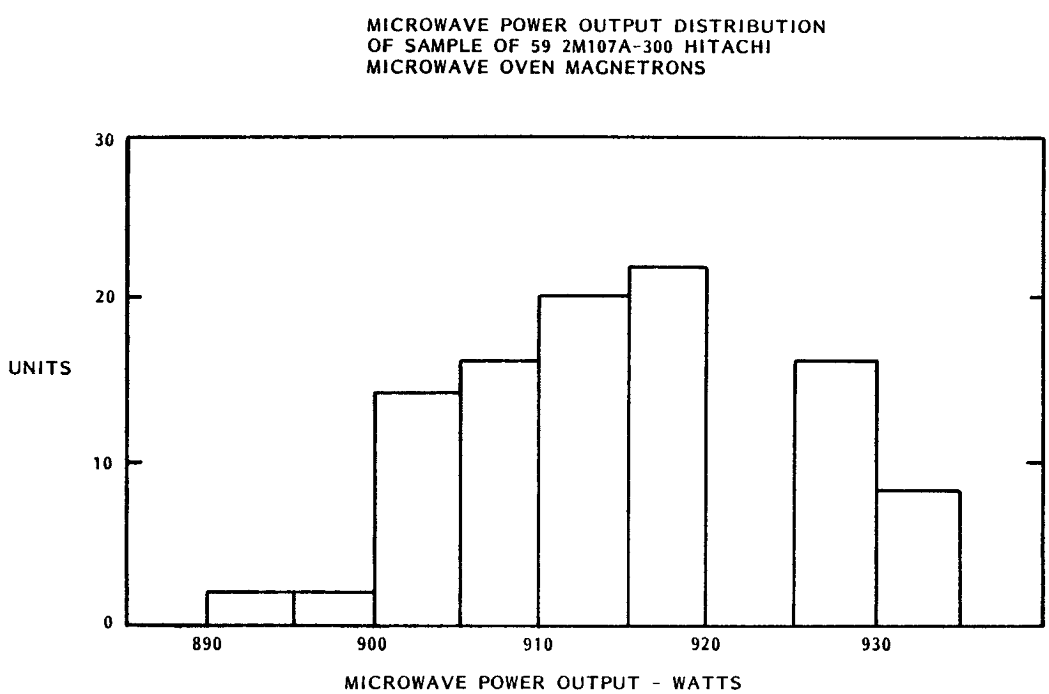


Figure 37. Microwave Power Output Watts

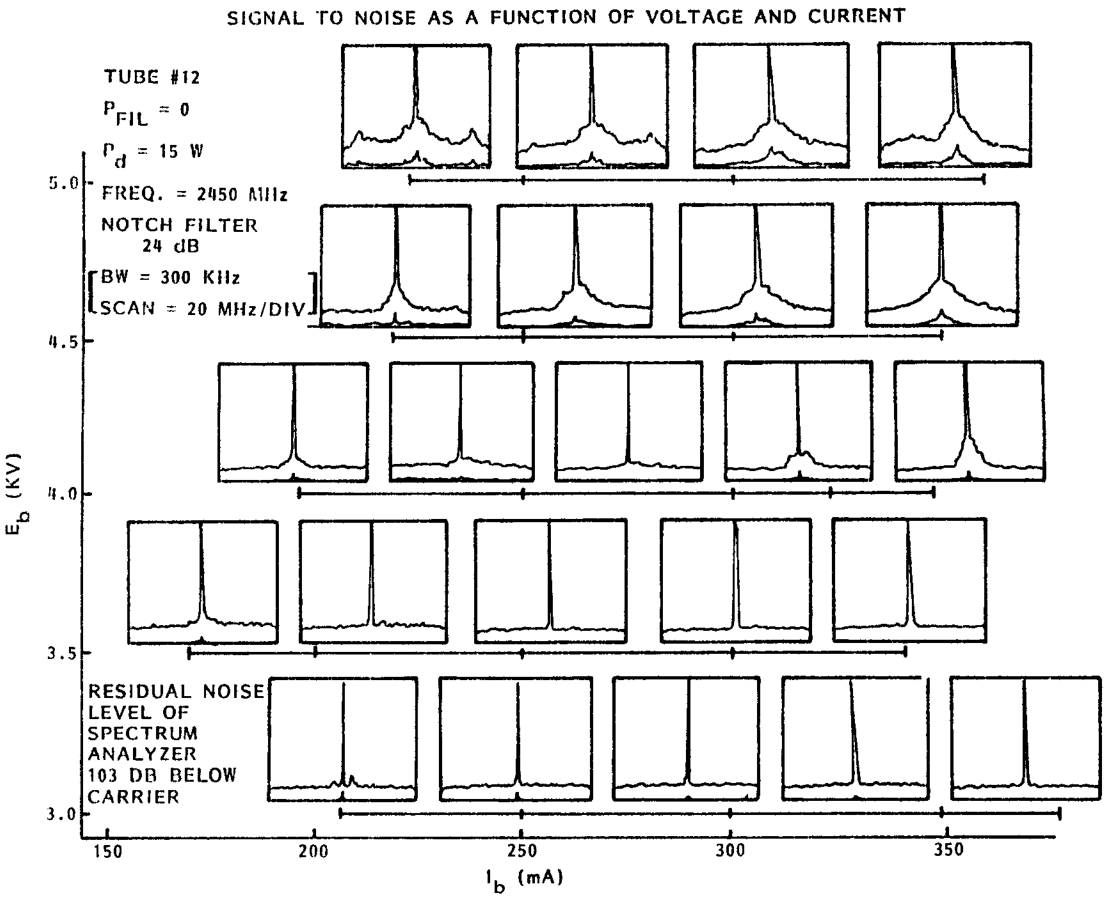


Figure 38. Magnetron Signal to Noise

Harmonic Generation

Measurements of harmonic power at the output of the magnetron were taken when operating into a 3/4" coax line to preserve single mode propagation. The data indicate that the harmonics were significantly below the main output. The measurements obtained on two different magnetrons are given below.

Frequency	Harmonic Level, dB below Carrier Tube #11	Tube #12
f_o	0	0
$2\ f_o$	-71	-69
$3\ f_o$	-97	-85
$4\ f_o$	-86	-93
$5\ f_o$	-62	-64

These are relatively low power harmonics but they may still be too high to meet regulations.

The ruggedness of the microwave oven magnetron cathode has been well proven in the microwave oven where it is characteristically operated at higher temperatures to meet the peak current requirements imposed by the unfiltered output of a half wave rectifier. The feedback does not work under these conditions because of the thermal time constant of the cathode which is approximately one half second.

Power Transfer

The relationship between the power received at the rectenna depends on various factors as indicated in Table 24. The array losses include the scan loss, which depends on the subarray size and the maximum scan angle; the spillover loss for dish subarrays; and all other subarray losses. The propagation loss accounts for the atmospheric transmission loss particularly through precipitation. The beam efficiency defines the efficiency by which power available at the ground antenna is coupled to the rectenna. It depends directly on the rectenna area and inversely on the ground antenna spot size. It also depends on the rectenna illumination factor; this factor is one for uniform illumination and is less than one for a shaped rectenna illumination. The focused spot size (area) in turn depends inversely on the ground array area and directly on the square of the distance between the ground array rectenna. Uniform illumination and focusing produces a minimum spot size, but also produces highest side lobes.

TABLE 24. POWER TRANSFER

POWER AT RECTENNA = TOTAL TRANSMITTER OUTPUT
X LOSS TO RADIATOR
X ARRAY LOSSES (SCAN, SPILL-OVER, ETC.)
X BEAM EFFICIENCY (GROUND ARRAY TO RECTANNA)
X PROPAGATION LOSS

BEAM EFFICIENCY RECTENNA (AREA)/SPOT SIZE, RECTANNA ILLUMINATION FACTOR

SPOT SIZE ARRAY SIZE AND ARRAY RF PHASE ILLUMINATION FUNCTION

In Figure 39, the spot size (distance between the 1/2 power points) is shown in the Fresnel region as a function of the distance from the aperture. In the Rayleigh region, the focused beam resembles the beam as it would appear in the far field. In the Rayleigh region, the unfocused beam is contained, for the most part, within the parallel cylinder shown in Figure 39. The focus at the Rayleigh distance has about 80% of the energy concentrated in the spot.

The relationship between the beam efficiency for various types of ground and rectenna aperture types have been considered for the following: circular ground to circular rectenna, square ground to circular rectenna and square ground to square rectenna (unlikely). For a first approximation there is little difference between the focused circular and square ground antennas except for their sidelobes. The circular antenna has circular constant amplitude sidelobe rings much the same as is obtained with a circular hole light diffraction pattern. In contrast, the square aperture has peaks and valleys, where the peaks are much higher than those corresponding in the circular aperture patterns.

Rain attenuates microwave energy through the mechanisms of reflection and absorption (Ref. 44). Depicted in Figure 40 are the transmission efficiency through rain of various intensities. In the northern temperature zone rain above 25 mm/hr are of extreme low probability. Extrapolating between the curves indicates that frequencies up to 6 GHz could be used. In the tropic region, short duration rains of up to 50 mm/hr can be expected. The frequency is limited to S-band under such severe precipitation.

Safety and Interference

The safety and interference issues relate to the possible effects of CO-OPS on the surrounding environment. Except in the immediate vicinity (at antenna radiating surface) there is no danger to wild life or personnel. Interference with communication is restricted by government regulations; therefore, CO-OPS will need to include filters in the transmitter output to meet these regulations. The rectenna does have spurious out of band reradiation and this too is highly controlled and must be brought to an acceptable level.

GOVERNMENT USE FREQUENCY ALLOCATIONS

The regulations for the ISM operation are summarized in Table 25. By far the most stringent is the harmonics or spurious requirements Ref. 43).

EMI Required Performance Improvements

The performance improvements necessary to meet the EMI specifications are tabulated in Table 26. The transmitter improvement is within the state of the art and therefore is of little concern. The rectenna improvement is

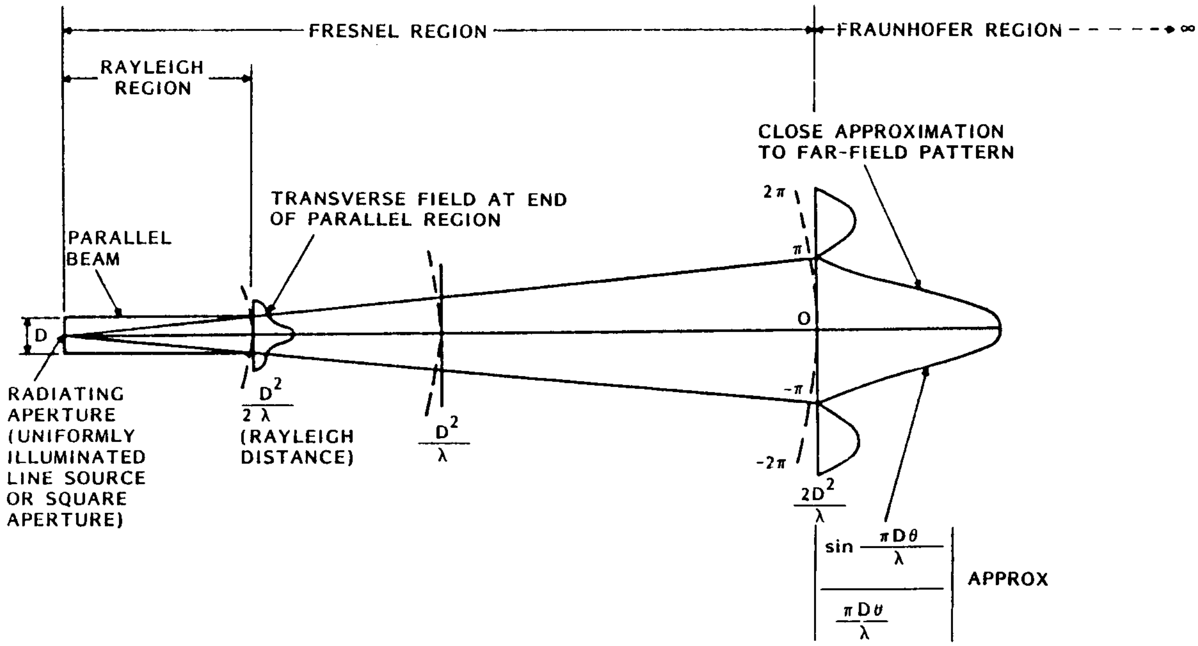


Figure 39. Parallel Beam Region Within Fresnel Region

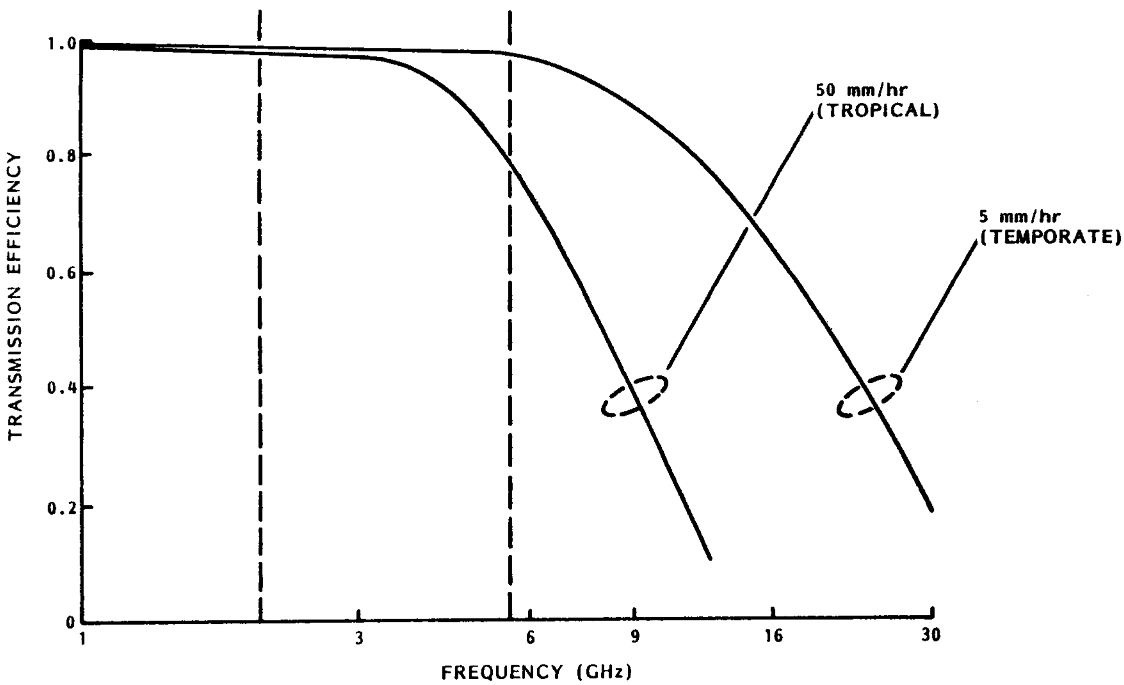


Figure 40. Transmission Efficiency Molecular Absorption and Rain

TABLE 25. GOVERNMENT USE FREQUENCY ALLOCATION

NATIONAL TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION (NTIA) FREQUENCY DESIGNATIONS FOR INDUSTRIAL, SCIENTIFIC AND MEDICAL (ISM) EQUIPMENT INCLUDE:

2450 MHz ± 50 MHz

5800 MHz ± 75 MHz

NO FURTHER AUTHORIZATION IS REQUIRED IF THE FOLLOWING RESTRICTIONS ARE MET:

HARMFUL INTERFERENCE TO ANY AUTHORIZED RADIO SERVICE OUTSIDE THE ISM BAND IS ELIMINATED

ENERGY AND BANDWIDTH SHALL BE REDUCED TO A MINIMUM (DOES NOT INCLUDE INDUSTRAL HEATING EQUIPMENT)

HARMONIC OR SPURIOUS OUT-OF-BAND RADIATION-25 uV/M TIMES THE SQUARE ROOT OF RF POWER RADIATED/500 AT 1000 FEET BUT NOT TO EXCEED 10 uV/M AT ONE MILE

MARSHALL SPACE FLIGHT CENTER IS AUTHORIZED TO USE ANY RADIO FREQUENCY FOR <u>SHORT</u> OR <u>INTERMITTENT</u> PERIODS PROVIDED THEY DO <u>NOT</u> CAUSE HARMFUL INTERFERENCE TO AUTHORIZED SERVICES.

much more difficult to obtain but can be accomplished within the time frame of the CO-OPS program (5 years). There is also some question about the level of second harmonics being a function of the diode design. A combination of diode selection and addition testing should resolve this problem.

TABLE 26. EMI REQUIRED PERFORMANCE IMPROVEMENTS

GROUND SYSTEM

-	OUT OF BAND	-	90 DB KLYSTRON
	SPURIOUS	-	70 DB MAGNETRON
-	RF FILTERING	-	30 DB REQUIRED
-	EFFECT	-	1 DB ADDITIONAL LOSS

RECTENNA

-	CROSS PRODUCTS	-	-30 TO -60 DB*
-	SECOND HARMONICS	-	-30 TO -80 DB
-	RF FILTERING	-	SECOND HARMONIC 48 DB IMPROVEMENT
-	CROSS PRODUCTS FILTERING	-	30 TO 50 DB IMPROVEMENT

* Subsequent investigation by the Canadians has shown cross products can be eliminated with proper design.

Ground System Costing

The cost factors upon which the CO-OPS system depend are described in equation form in Figure 41. The first two lines are the RDT&E costs while the third line is the life cycle costs for both the prime power and for O&M over a 10 year period. A Slotted Array to Circular Rectenna cost data is shown in Figure 42 to illustrate suitable sizing and costing.

6.4 Airborne Rectenna Characterization

The major design rectenna issues are which design dual polarization technique to use, which diode should be selected both from its power limitation and cost and from its ability to not produce spurious radiation, and, lastly, which low loss material to use to construct the rectenna. The latter is resolved by using Kapton F.

Rectenna Considerations

The rectenna design considerations are noted in Table 27. The maximum power density is prescribed by the diodes employed. This value however does not produce long life in the diodes so a lesser value of about 500 watt square meter is preferred. The remainder of the

COST = AREA DEPENDENT COST + POWER GENERATION COST
(ANTENNA) (TRANSMITTER)

+ POWER DISTRIBUTION COST (PRIME POWER + COHERENT MICROWAVE REFERENCE SIGNAL)

+ ENERGY COST OVER LIFE CYCLE + MAINTENANCE COST OVER LIFE CYCLE

Figure 41. Ground System Costing

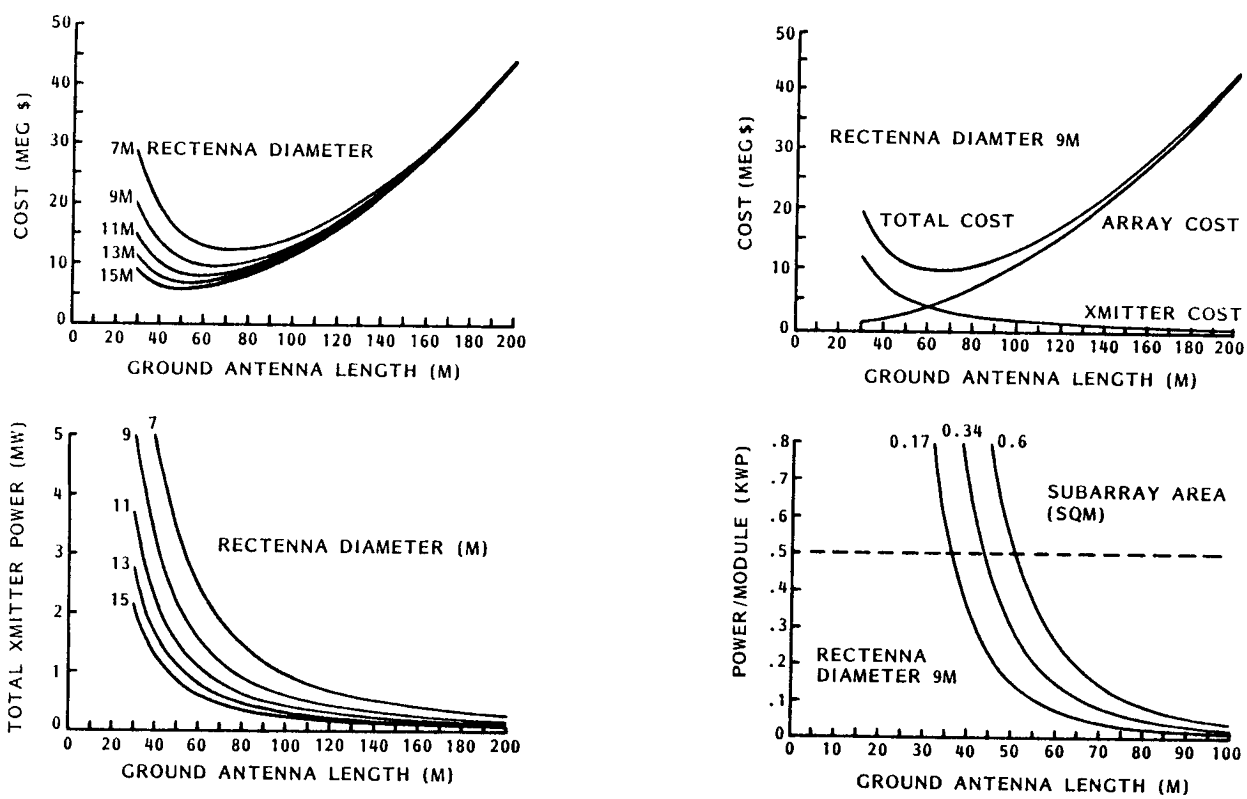


Figure 42. Square Slotted Array to Circular Rectenna

TABLE 27. RECTENNA CONSIDERATIONS

MAX POWER DENSITY	1100 W/M^2
AREA SHAPE	NO LIMITATION EXCEPT BEAM EFFICIENCY
AREA SIZE	DEPENDENT ON POWER DENSITY AND AIRCRAFT/ PAYLOAD DESIGN
POLARIZATION	DUAL REQUIRED TO PREVENT POLARIZATION NULLS
CONVERSION EFFICIENCY	80 PERCENT DESIRED

considerations are general in nature, but are necessary to assure high efficiency performance.

Polarization

The two methods of receiving polarization are illustrated in Figure 43. The efficiency of the dual linear type was measured by the Canadians and found to be less than the 80 percent goal. Measurements on both configurations are recommended in phase A.

Diode Selection

Rectenna diode selection is an important consideration for CO-OPS and is summarized in Table 28. The power level is set based on the nominal value expected. However the diode must also be able to handle levels of twice this nominal. Available diodes used in the construction of rectenna are indicated along with power capability and cost. The silicon diode has, when used by the Canadians, shown good spurious noise performance, but its power level is too low. The Canadians have paralleled up to nine of these diodes. The cost shown for the silicon diode does not include cost of multiple parallel diode mounting.

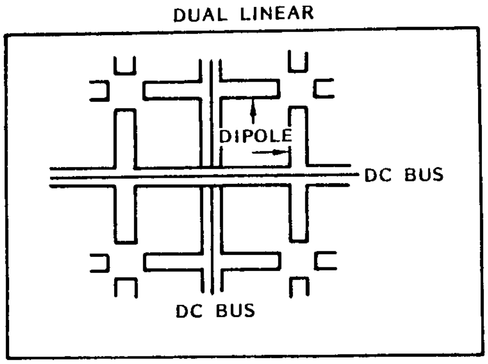
6.5 Airborne Thrust Generation Characteristics

Rotating Component Sizing Methodology

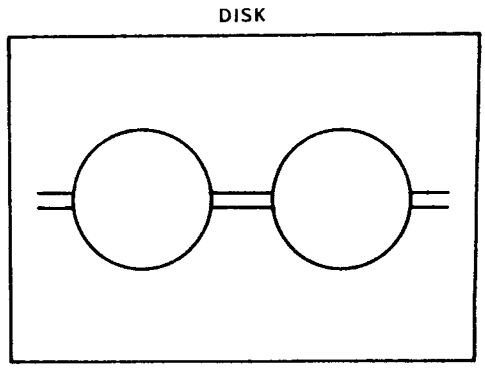
The platform power train methodology was designed to calculate platform size and power required based on previously calculated drag numbers. Inputs are cruise dynamic pressure, q, wing area, S, total drag coefficient, C_d, cruise true airspeed, V, and highest wind speed expected to be encountered, V. Calculations provide thrust power required, power train mass and microwave power required at the rectenna.

The methodology begins by initializing propeller efficiency. Next, several descriptors may be used to begin an estimate of motor, controller and gearbox efficiencies. Rectenna efficiency may also be calculated.

Power train component mass factors are initialized instead of being calculated. First, it is necessary to calculate thrust power required based on the drag estimate, microwave power required and the incremental power flux density required if winds encountered are greater than zero. Next, rectenna area may be corrected for bank angle. Finally, power flux density required at the rectenna may be calculated and should include payload and auxiliary power requirements. The value of power flux density is tested against an arbitrary upper limit (currently 600 watts per square meter) and the rectenna may be resized if necessary to bring power flux density to the test value. This test value will be discussed in a later part of this section. Following this, power train mass may be calculated.



- DUAL SHEET
- EFFICIENCY NEEDS TO BE MEASURED



- SINGLE SHEET
- EFFICIENCY NEEDS TO BE MEASURED

Figure 43. Polarization

TABLE 28. DIODE SELECTION

CRITERIA	COMMENTS
POWER LEVEL	4 W NOMINAL - TO KEEP RECTENNA AREA MINIMUM
RELIABILITY	30,000 HRS MIN - FAIL SAFE DESIGN - SHORTS DO NOT DOMINO
SPURIOUS	MUST MEET EMI REQUIREMENTS

AVAILABLE

	POWER	COST
GALLIUM ARSENIDE (GaAs)	UP TO 8 W	$20 PER DIODE
SILICON	1/4 W	$1 PER DIODE*

* DOES NOT INCLUDE COST OF MULTIPLE PARALLEL DIODE MOUNTING

Rotating Component Performance

Figure 44 is a summary chart which describes the relationship of motor operating characteristics to design parameters such as mass, efficiency and power. Results of work to date show that motor efficiency is highest and mass lowest at high design motor speeds as shown in the figure. Propellers, however, must be large in diameter to be efficient at low speeds and, hence, must turn slowly. This dichotomy between motor and propeller operating speeds can be accommodated by using a gearbox with two stages of reduction. Table 29 addresses gearbox efficiencies and masses.

TABLE 29. GEARBOX PARAMETERS

POWER (HP)	LENGTH (CM)	WIDTH (CM)	HEIGHT (CM)	MASS (KG)	EFFICIENCY (%)
10	16.51	17.27	17.27	12.61	98.5
20	17.27	24.89	24.13	24.13	98.5
30	21.59	29.21	27.94	41.15	98.5
50	23.37	35.05	31.75	54.61	98.5

Rotating components used here are virtually identical in powers and efficiencies to those used in Ref. 12.

The CO-OPS platform power train is composed of rectenna, power conditioner, motor, motor controller, gearbox and propeller. Past published work (Ref. 12) established a conceptual characterization of the motor/controller/gearbox combination and that work has indicated that high efficiencies are possible within the current state-of-the-art. Figure 45 presents motor efficiency as a function of maximum motor design speed. As Table 29 showed, design motor speed will be high (8,000 rpm) to minimize motor mass. The corresponding efficiency will be around 93.9% as can be seen in Figure 45.

The propeller to be used on the CO-OPS platform will be carefully designed to produce maximum efficiency at cruise conditions. As discussed in Ref. 12, the propeller will be designed for minimum induced loss and will probably have an efficiency around 85%. It will be capable of operation over a range of thrust powers in order to provide climb and maneuvering capability, but efficiencies will be less than for the design condition.

The power controller accompanying the brushless DC motor will have an efficiency of around 99% (Ref. 12). Combining motor efficiency, controller efficiency and gearbox efficiency with a propeller efficiency similar to that used in Ref. 12 produces a design point efficiency for the rotating components of around 79%.

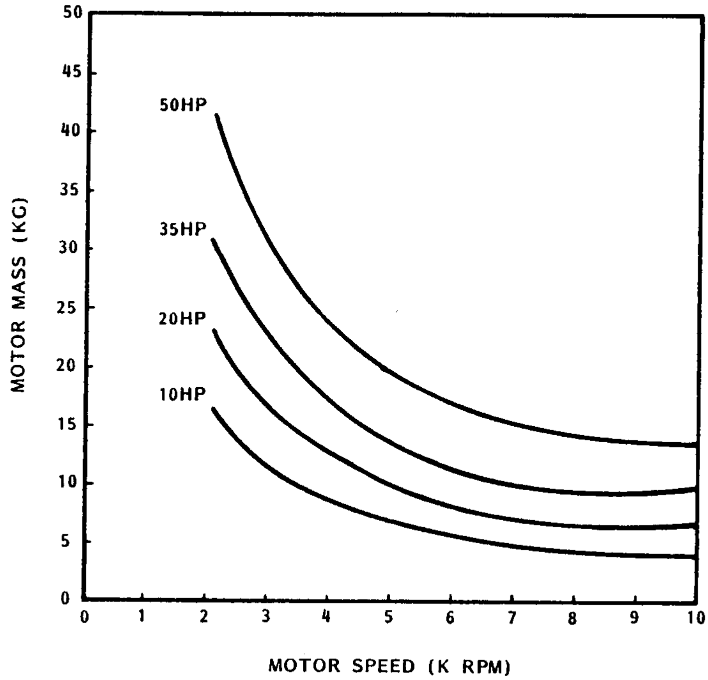


Figure 44. Motor Mass Vs. Motor Speed

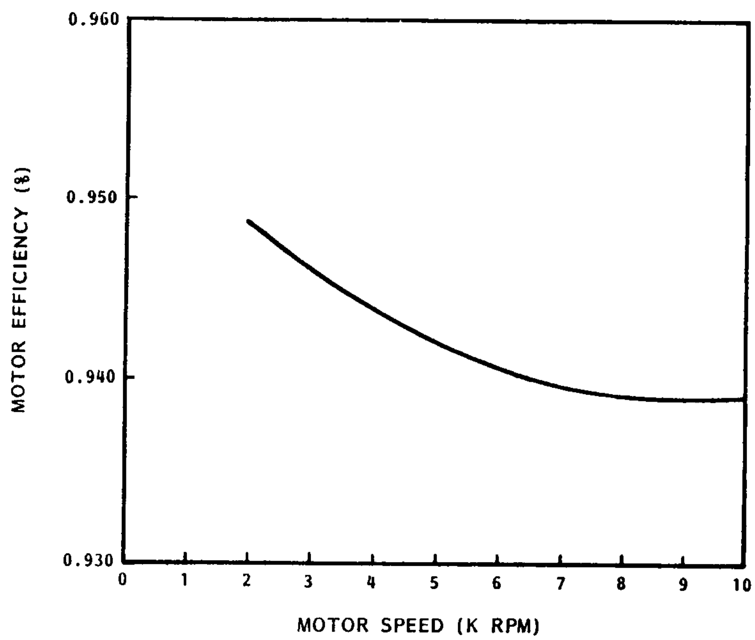


Figure 45. Motor Efficiency Vs. Maximum Design Speed

Since all of the rotating components except for the propeller are designed to run most efficiently at maximum power, it is a fair assumption that they will be running off this design point most of the time in order to maximize propeller thrust. Figure 46 presents the decrement in efficiency expected from running the motor/controller at partially rated power. It can be seen that partial power operation cuts rotating component efficiency to between three-fourths and four-fifths of the rated number. Proper matching of rotating component designs will minimize the penalty paid for off-design point operation and will maximize cruise efficiency.

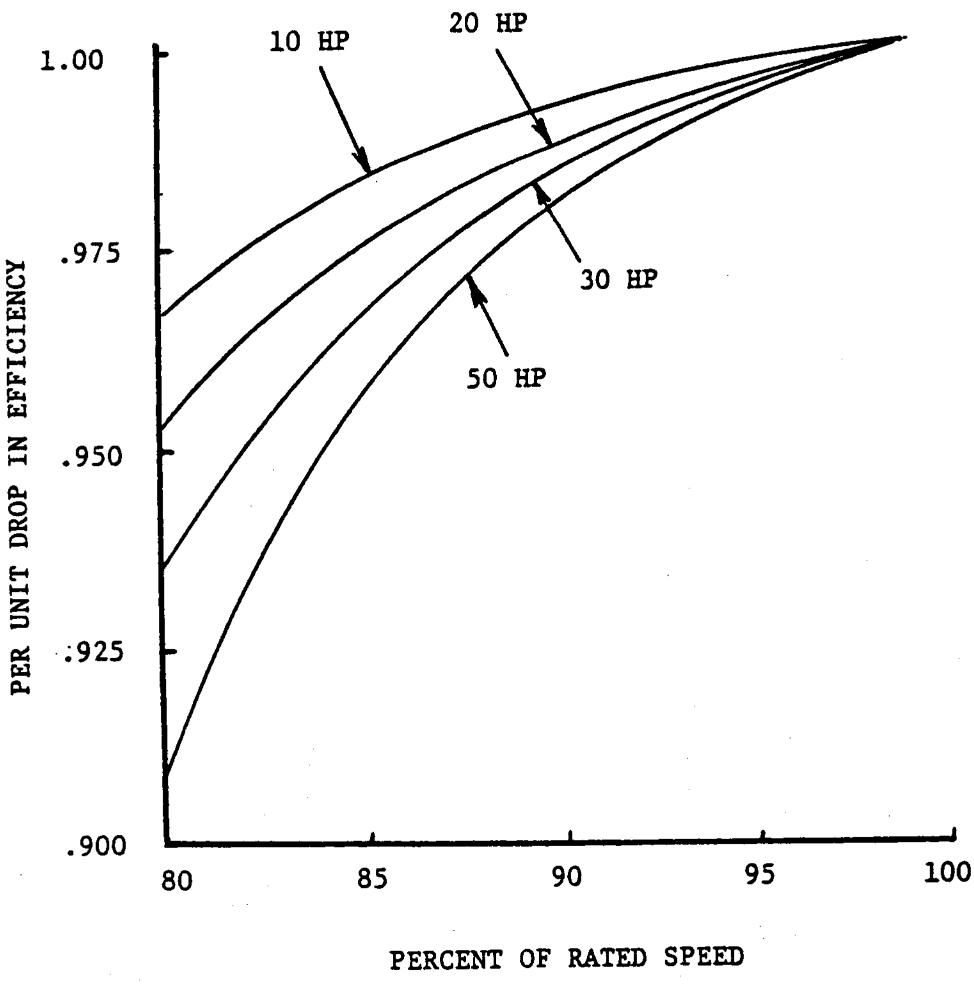


Figure 46. Drop In Motor-Controller Efficiency Vs. Percent Loss in Motor Speed

7.0 DATA SUBSYSTEM

7.1 Overview

The Data and Control subsystem serves two functions. It provides the data downlink in the aircraft; and on the ground, the storage media and retransmission media for the scientific data collected by the CO-OP's payload instruments. Another function served by the Data and Control subsystem is flight control. In this role it performs three tasks. One is providing the aircraft positional data with which to maintain the aircraft flight within the cone of coverage defined by the scan limits of the ground antenna. Another is to supply data either by direct measurement or from instrumentation in the aircraft by which to control the ground radiated power in order to sustain flight in wind environment and to prevent the rectenna microwave diodes from reaching temperatures that would significantly compromises their operational life.

A data rate of 30 kb/sec is needed at site one to satisfy the peak needs for the scientific data downlink. This worst rate is considered modest with today's technology. If we allow the requirement to become a factor of 3 greater, then the downlink has ample room for growth and for the use of redundant data or error correction codes. A number of datalink suppliers were contacted to determine whether the downlink could be coupled with an uplink with the same capability and whether both were available with off the shelf hardware. The answer was affirmative for 10 kB/sec uplink/downlink.

Table 30 shows a list of the various equipment required for the uplink/downlink. To insure high availability during the two to six month mission, almost all equipment has been made redundant. This also includes the aircraft mounted spiral antennas. The availability under these circumstances is expected to be 99 percent or higher for the airborne equipment. The cost of the redundant system was in the range of between $200K and 250K.

These costs do not cover the cost of the ground system data storage, conditioning, and retransmission. The latter two at this point are not defined and could be customized for each of the individual types of sites. For example, the Arctic site probably would use satellite communications while stations in this country might resort to manual delivery. These are both options at this point and not recommendations. However, the conditioning and retransmission is finally implemented at a site, each will not be a cost driver when compared with the ground power antenna and transmitters.

Storage media are readily available to accommodate the 390 KB/sec expected for the scientific data. This is well below the Direct Memory Access (DMA) capabilities of almost all computers today including PCs. Because the rates are so low, there are numerous options open for designing a storage system for this application. Consideration will be given to using tapes, hard disks, floppy disks and/or the optical disks with their ability to store megxmegabits of data. It is equally conceivable to do the

TABLE 30. DATA SYSTEM APPROACHES-PLATFORM/GROUND SYSTEM

FLIGHT CONTROL SENSORS
- ON BOARD RECTENNA POWER SENSORS
- GROUND TRACKER

BEAM POINTING SENSORS
- RETRODIRECTIVE
- ON BOARD RECTENNA POWER SENSORS
- MONOPULSE TRACKER

POWER CONTROL SENSORS

- ON BOARD DEMAND SENSOR

- GROUND TRACKER A/C VELOCITY AND WIND VELOCITY SENSOR storage job using a gang of 3.5 inch floppies or with any other of the storage media mentioned in combination or alone. A computer would be used to control them. Which will be best for this time because of rapidly changing cost and capabilities in all the various types of disks. Growth is also expected in the PC capability in the next few years.

In all, the cost of the data communications package required to accommodate the scientific data is not a significant cost driver; all together, it is expected to represent no more than 3 to 4 percent of the total CO-OPs system acquisition.

7.2 Control Functions

The requirements for the three control functions are summarized in Table 31. The ground antenna output must be capable of being varied. A reasonable goal for its function is the indicated 60 percent from the nominal specified for the no wind case. This value should provide sufficient reserve to enable flying the aircraft up the ground antenna coverage to station keeping altitude.

Beam pointing requires an accuracy sufficient to limit the rectenna illumination taper loss because of the beam steering error to less than 10 percent. A beam pointing accuracy of 10 percent of the focused beam or spot diameter at the rectenna will satisfy this need. For a typical array 70mx70m the required beam pointing accuracy at 20 KM is 0.01 degrees. Keeping the aircraft in the cone of coverage of the ground antenna requires measuring and predicting the aircraft's position. The accuracy required for this function depends on the scan limitation of the ground antenna and the flight profile within the particular scan coverage. For example, pedestal mounted dishes or arrays can have a scan coverage of 45 degrees from vertical. The flight path could be contained within say a 40 degree cone. For this case, the aircraft measurement accuracy need not be better than 4 degrees. The fixed slotted array antenna, on the other hand, will have a scan coverage limitation of about 6 degrees. The measurement accuracy required for this situation is 0.6 degrees for both azimuth and elevation relative to ground antenna.

Although of secondary importance, the range of the aircraft to the ground must also be measured. An accuracy of 10 percent is sufficient.

Power Control Approaches

Table 32 lists the various power approaches being considered for CO-OPs. The magnetron cannot reduce the input rf power as can the linear rf amplifiers. The reason for this is that magnetron is being used as a phased locked oscillator and requires a certain input rf signal to perform this function. If the input power is reduced to below this minimum value the magnetron will become a free running oscillator. With each magnetron in the array free running the array will not focus.

Defocusing the array will reduce the power at the rectenna by increasing the spot size. If carried to an extreme, it will also increase

TABLE 31. STEERING AND FOCUS CONTROL REQUIREMENTS

CENTRAL		DISTRIBUTED	
MEASURE:	ANGLE RANGE	MEASURE:	PHASE GRADIENT
CALCULATE:	STEER FOCUS	CALCULATE:	NEGATIVE GRADIENT
CONTROL:	PHASE OVER APERTURE	CONTROL:	PHASE OVER APERTURE

TABLE 32. POWER CONTROL

	RECTENNA	BATTERY	REASON TO CONTROL POWER
			(1) EXCESS POWER INPUT WILL REDUCE RECTENNA LIFE
	POWER	DATA LINK	(2) REDUCE OPERATING COSTS
POWER OUTPUT	GROUND SYSTEM	POWER CONTROL	

POWER CONTROL

METHOD	MAGNETRON	KLYSTON	SOLID STATE
CHANGE FREQUENCY	X	NO	NO
REDUCE INPUT RF	NO	X	X
DEFOCUS ARRAY	X	X	X
TURN OFF SELECTED TRANSMITTERS	X	X	X

the sidelobes. This approach is wasteful of energy since it requires the same input power to the ground system regardless of situations where less power is required at the rectenna.

A method to control the output power and not waste energy is the last approach in Table 32, turn off selected transmitters. If done in a quasi-random manner, this approach will produce no deleterious effects. The random placement of the turned off transmitters in the array prevents any significant increase in the antenna sidelobe magnitudes.

Steering and Focus Control

Two approaches to steering and focused control have been considered for CO-OPs. One uses a centralized single angle and range measurement to develop the aircraft position data. This data is then used to generate the individual steering and focus phases for each subarray. The other uses an interferometer to measure the phase gradient at each subarray and performs local corrections. Range and angle data are required to compute the focus phase for this latter approach. A comparison of the salient features of each of theses approaches appears in Table 33.

The central is favored at this time since it not only provides the data necessary for steering and focusing, but the same data could be used to control the aircraft flight.

TABLE 33. STEERING AND FOCUS CONTROL

	CENTRAL		DISTRIBUTION
MEASURE:	ANGLE RANGE	MEASURE:	PHASE GRADIENT
CALCULATE:	STEERING & FOCUS FOR EACH SUBARRAY	CALCULATE:	NEGATIVE GRADIENT
CONTROL:	PHASE OVER APERTURE	CONTROL:	PHASE OVER APERTURE
APPLICATION:	ALL ANTENNA ARRAY APPROACHES	APPLICATION:	RESTRICTED TO LARGE AREA SUBARRAYS I.E. CENTER
EQUIPMENT:	TRIANGULATION USING TELEMETRY DOWNLINK ANTENNAS	EQUIPMENT:	ACCURATE PHASE INTERFEROMETER
RELATIVE COST	1.0	RELATIVE COST	1.5 - 3.0 (HIGHER)

An example of the distributed approach is shown in Figure 47. A distributed retrodirective array measures the received differential phase front from a beacon in the aircraft and radiates the complex conjugate of that phase front. The beacon wavelength must be larger than the element spacing to measure the differential phase front unambiguously. Accurate phase control must be maintained through the receiver and up-conversion to the array frequency to ensures tolerable beam steering losses in the power transfer to the aircraft.

An example of the central control is shown in Figure 48. Central control requires measurement of range and angle to a beacon signal radiated from the aircraft. The measured angle is used to develop row and column steering commands. The range information is used to develop a set of row and column focus commands. The set of weighted row and column commands is distributed over the array along with timing and control signals. At each intersection a small processor develops the phase command for that location and applies it to the phase control element as appropriate.

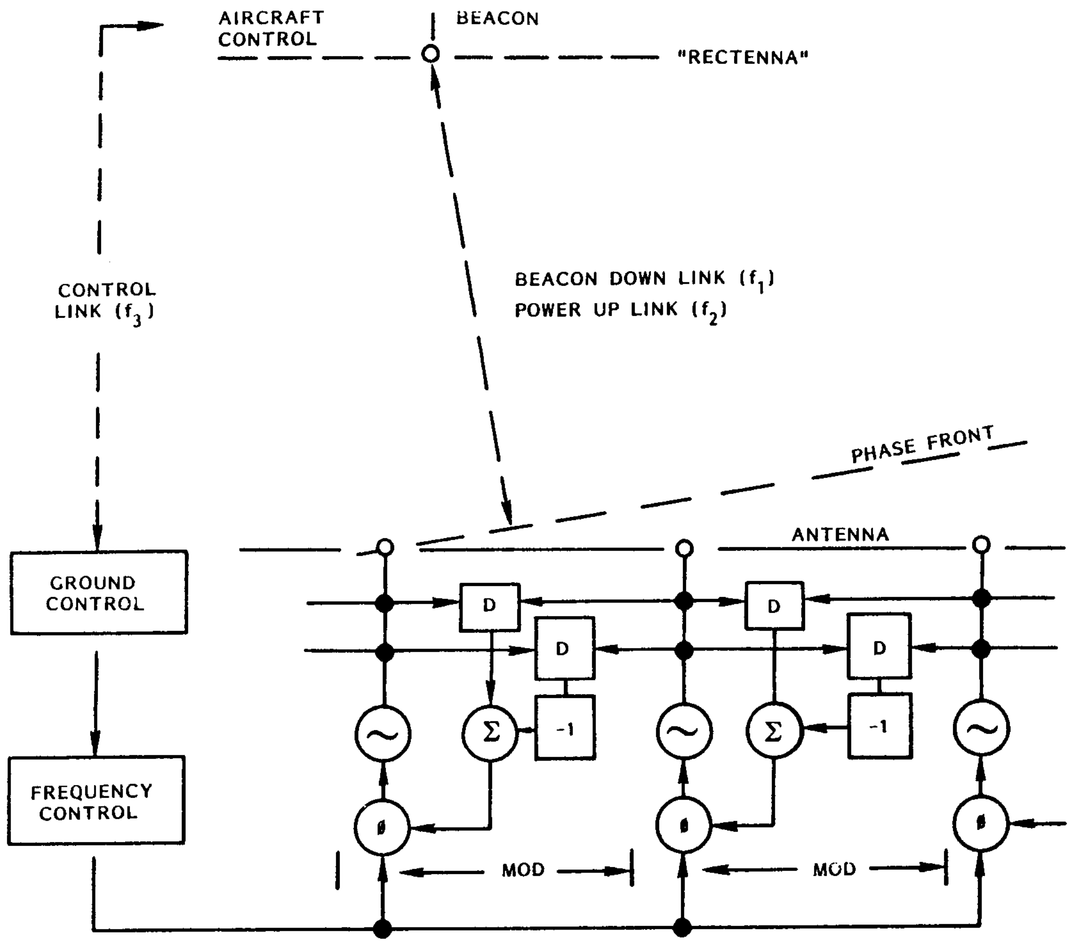


Figure 47. Distributed Retrodirective Array Control

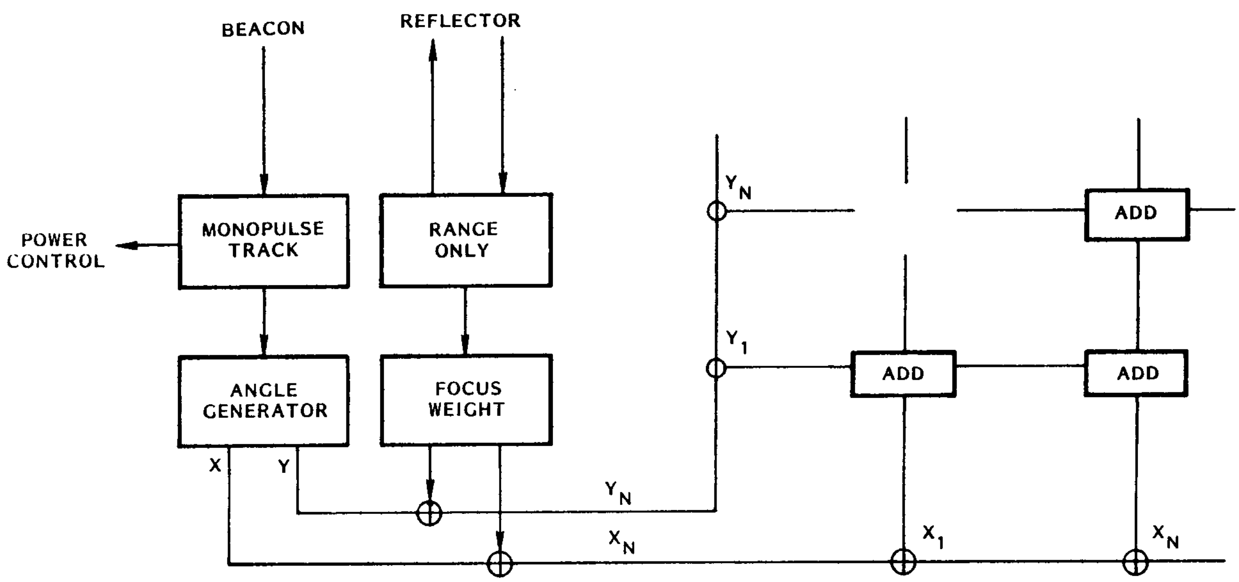


Figure 48. Central Control

8.0 SYSTEMS ENGINEERING AND INTEGRATION

8.1 Overview

This CO-OP System feasibility study started with a large number of combinations of possible subsystems and component performance parameters, all with their associated impacts on system performance, cost and schedules. It was the distilling of these options to several viable systems which was the essence of this pre-Phase A study. The major categories of options are presented in Figure 49 which also shows the parametric convergence used during this system study. Platform subsystem options were in the tens of thousands by the time all viable combinations of basic geometric ground and platform subsystem parameters were considered. Ground antenna subsystem options, while not as numerous as platform subsystem options, had many variations in component hardware.

Some subsystem options could readily be ruled out for detailed consideration in comparison with other subsystems. Others were only shown to be less viable after consideration in full systems. The parametric system sizing methodology used during this study was characterized by its flexibility in modeling these diverse combinations of options.

Mission Description

The purpose of CO-OPS is to verify system capability to operate in the upper atmosphere continuously for months at a time over a long period (up to 10 years). The CO-OP System will be capable of operating at a variety of sites with similar environmental conditions. Five site categories have been examined during this study. The primary mission will take place at the prototype verification test site which will probably be Site 1, NASA/MSFC.

The potential recommended payload complement will be a variety of climatological sensors which were originally specifically chosen for a (Ref. 1) satellite payload. Refer to section 5 for a detailed discussion of sensor options. All payloads have been considered user-supplied for costing purposes.

Concept Description

The system concept used during this study is a combination of airborne platform and ground-based antenna. In the nomenclature of this study, the platform subsystem carries the payload subsystem and part of the data subsystem and orbits over the ground subsystem antenna. The ground-based antenna is a modularized phased array made up of many small elements supplying a few hundred watts of power each. Its collective power is focused into a conical shape, generally circular when it is vertical. Power is beamed to the platform where a doubly polarized rectenna on its undersurface collects some fraction of the beamed power and converts it to electricity for distribution throughout the platform. Figure 50 presents a diagram of this generic configuration. Power transfer capability is

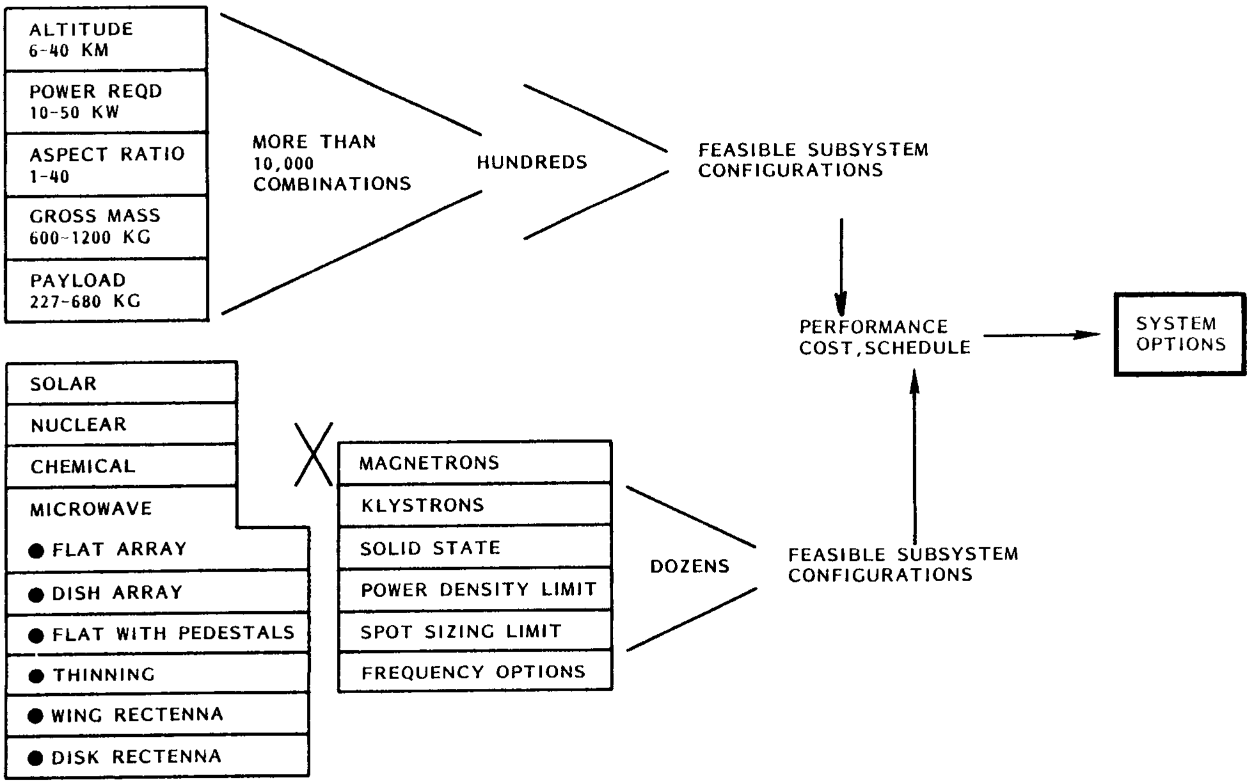


Figure 49. Schematic of Parametric Convergence Showing Major Options Considered

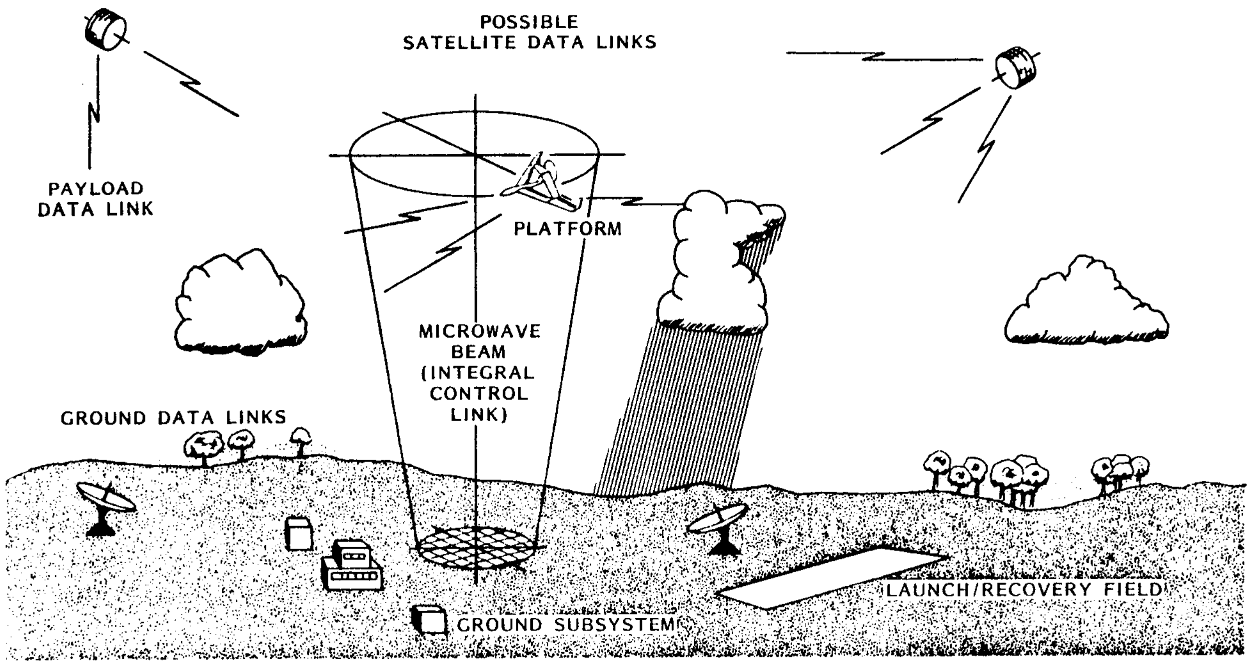


Figure 50. Generic Microwave Carbon Dioxide Observational Platform System

reduced by off-vertical alignment as the platform maneuvers, possibly forcing an active control system on both the platform and ground subsystems. This collected power must be carefully monitored and conditioned to provide the best combination of voltage and current to run the propulsive motor, payload, guidance and navigation and platform communications and control equipment.

The ground subsystem provides antenna beam steering capability to focus the beam on the rectenna as the platform maneuvers. Both angular and range focus are provided.

The type of platform modeled is a heavier-than-air subsonic remotely piloted vehicle. For operations, the platform will be assembled and serviced at the ground subsystem site. It will be towed aloft to a high enough altitude that it can collect sufficient power in the beam to continue climbing to its operational altitude of around 20 km (65 600 feet). Large portions of its flight may be pre-programmed and only certain phases, those most critical to fulfilling mission payload requirements, will be flown in real time from a nearby ground station. The platform will be recovered under its own power as it circles down through the beam until it is low enough to glide power off to a landing at the nearby recovery site. Routine maintenance will be performed at the launch/recovery site and payloads may be replaced as required to meet changing DOE observational objectives.

8.2 System Sizing Methodology

The system sizing methodology developed for this study is a combination of subsystem sizing methodologies for platforms and for ground antennas. The methodology links these two subsystems through the platform rectenna by equating power available at that point with power required. Each subsystem methodology will be discussed separately before system parametrics are discussed.

Background Theory

Historically, the design of microwave beam sources for high-altitude platforms was based on NASA-supported evolution of slotted waveguide arrays, which were developed for the Solar Power Satellite (SPS), into an electronically steerable phased array for microwave powered platforms. Other approaches, arrays of mechanically steerable dishes or thinned slotted arrays, have been evaluated and compared with the historical approach. To complete this comparative evaluation process, a more general expression for rectenna power output has been evolved that takes into account the large number of parameters involved in ground based transmitters and antennas.

To understand the need for this, it is instructive to discuss the expression which has historically been used to relate the parameter of greatest interest at the platform, DC power output from the rectenna, to the ground based antenna which is treated as a contiguous and uniformly illuminated assembly of radiating modules. Then the expression will be modified to reflect the impact of a large assembly of mechanically steerable arrays. The impact of a change in frequency will also be discussed. Next, the general expression for DC power flux density at the rectenna will be presented and, last, the various factors in this equation will be discussed.

Before doing this, however, a legitimate concern to be acknowledged is whether an expression for rectenna DC power flux density is the key to developing a cost analysis procedure applicable to microwave power transmission systems. Minimization of life cycle costs, and certainly minimization of initial cost, results in a power "spot size" in space that is considerably larger than the collection area available on a small platform. A minimum cost system for this particular application of microwave power transmission is an inefficient system in terms of the ratio of DC power output at a platform to microwave power radiated from a ground antenna. The resulting spot size will be large enough that platform power requirements can be met to a first approximation by making the rectenna area equal to the platform power requirement divided by the rectenna DC power output power flux density. If the platform has a very high aspect ratio and the rectenna is on the wing, there may be a significant falling off in DC rectenna power flux density along the wing which will have to be taken into consideration.

From the viewpoint of both low life cycle cost and low first system RDT&E costs of the microwave power transmission system, low rectenna DC power flux densities are needed. Can the DC power flux density of the rectenna be related to the platform's requirements? The relationship depends upon the platform design approach. The platform needs low wing loading to minimize propulsive power requirements. With an underwing rectenna, a DC power flux density in the neighborhood of 600 watts/meter2 will be required. On the other hand, if the rectenna is mounted within an external circular disc, then parasite drag must be minimized by striving for a high value of microwave power flux density--so high, in fact, that rectenna power input limitations may be encountered as well as driving up the cost of the microwave transmission and reception subsystem.

Historical Expression

Historically, a simplified expression has been used for rectenna DC power flux density output as a function of total area and total radiated microwave power from a square, flat phased array consisting of a large number of contiguous and uniformly illuminated modules. This expression, which also assumes uniform illumination of the entire antenna, was

$$\text{Pd rectenna} = \text{Pantenna} * \text{Aantenna} * \text{nrectenna} * \text{h2}/\lambda \qquad (8.1)$$

Previous work has discussed the loss in received power when the rectenna is located at a finite off-boresight angle (Ref. 29). This loss depends upon the angular antenna pattern of the radiating module (usually referred to as the element pattern) which in turn depends upon its physical dimensions. However, there are other losses for a flat phased array due to atmospheric conditions and antenna grating lobes. In addition to the introduction of mechanically steerable Reflectors, a possible change in frequency from the 2.45 ghz ISM band to the 5.8 ghz ISM band was considered. Higher frequency introduces atmospheric attenuation as an important parameter to be studied but may allow reduction of overall subsystem size while reducing side lobes.

General Expression

The general equation for power transfer between the ground system and rectenna is as follows:

Pdrectenna= (Pantenna*Aantenna*Srectenna)*nrectenna*ndistribution/ q2* h2*ngrating*nscatter*nillumination*npattern*namplitude*) (8.2)

The term in the power coupling equation

Pantenna*Aantenna*hrectenna/q2* h2 (8.3)

has been shown by Goubau to be a controlling factor in the efficiency of coupling power by focusing the ground antenna at the rectenna. Figure 51 shows Goubau's curve. Maximum power transfer may be achieved by increasing the areas in this factor. Practical restrictions, however, limit the areas as delineated in Table 34. Increasing this factor to its practical limit still may not mean a minimum cost system.

The transmitted power (Pantenna) is the sum of all microwave power developed in magnetrons or klystrons and distributed to an array. Options for microwave power are shown in Table 35.

The loss factor (rpattern) depends on subarray size and whether the subarray can be mechanically pointed at a rectenna. Table 36 indicates the dependence of this loss on these factors.

The fill factor ((fpack)antenna) is controlled by the spacing between array elements or, if subarrays and elements are used, between subarrays when the elements are contiguous in the subarray. Table 37 lists the dependencies of this factor on the various options available to provide antenna area.

Previously, in both cases, the only distribution loss (rdistribution) experienced was due to waveguide geometry. The slotted array had limited scan angle because one magnetron was associated with only one slotted array. By making the subarray smaller, the scan angle is increased permitting the platform to fly in a larger diameter circle thereby reducing its bank angle and any bank angle loss. However, the ensuing smaller subarray means that either magnetron power is distributed to a number of subarrays or less subarrays may be used and the overall array may be thinned. If the former is assumed, then power from a single magnetron would be fed to several subarrays and, hence, there is a distribution loss.

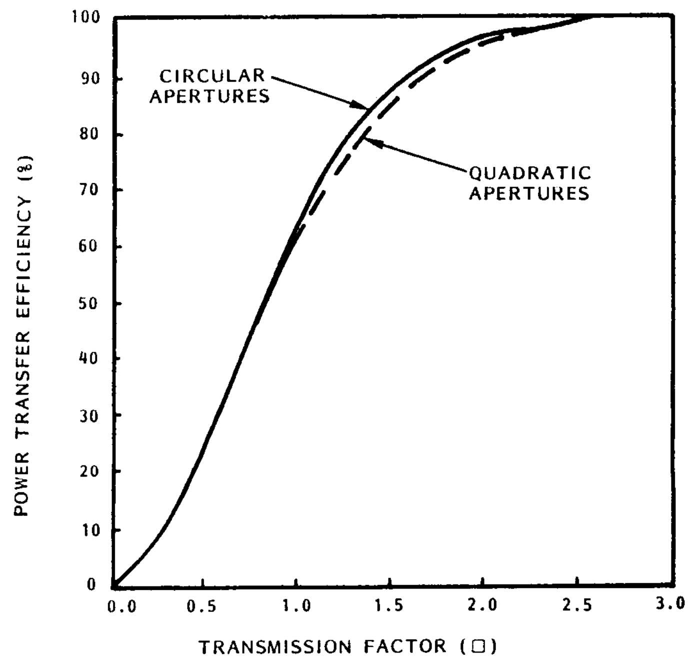


Figure 51. **Transmission Efficiency for Optimum Field Distribution in a Microwave Beam**

TABLE 34. PRACTICAL REASON FOR RESTRICTING THE TRANSMISSION EFFICIENCY FACTORY

$A_{antenna}$	Ground Antenna Area Available real estate 10^4 to 4×10^4 square meters is reasonable Thinning an array does not give the same results as increasing the area while increasing the number of contiguous elements. At best, the result at the rectenna is the same as with a non-thinned array.
$S_{rectenna}$	Rectenna Area Restricted by platform design. A fractional wing area circle may be assumed as a design entry point.
λ	Wavelength Currently 2.45 gigaherz is being used. Higher frequency reduces the ground antenna area for the same effect.
h	Altitude Around 20 kilometers selected as the minimum necessary.

TABLE 35. ANTENNA ARRAY OPTIONS

DEVICE	POWER OUTPUT	APPLICATION	COMMENTS
Magnetron	500-600 watts	slotted	Simple waveguide antenna feed for 0.8 square meter subarray RF distribution or smaller with phase shifter at each subarray.
Klystron	30 kilowatts	reflector	One transmitter per reflector.
Klystron	30 kilowatts	slotted	Requires RF distribution with phase shifter at each subarray.
Klystron	500 kilowatts	reflector	Requires RF distribution with phase shifter at each subarray.

TABLE 36. PATTERN EFFICIENCY DEPENDENCE

ARRAY TYPE	FOCUS METHOD	STEERING METHOD	$n_{pattern}$	COMMENTS
Reflector	Electrical Phase	Mechanical	1	Mechanical pointing eliminates this loss.
Slotted Array	Electrical Phase	Electrical Phase	cos 8	Varies with steering angle, 8

TABLE 37. PACKING FACTOR FOR A RECTANGULAR GRID

SUBARRAY SPACING	$(f_{pack})_{antenna}$	COMMENTS
λ/2	1	is wavelength
λ/2	$\frac{\text{subarray area total}}{\text{available array area}}$	

In addition, a phase shifter having a capability to safely transmit the subarray's share of magnetron power is required. Loss through this phase shifter is added to the distribution loss.

Development of Equations for Sizing Flat Slotted Arrays

Two types of microwave antenna may be used to radiate power to a platform rectenna: Dishes and flat arrays. This discussion applies only to flat arrays whose complete description is given in Ref. 3. To summarize, the flat array is made up of square elements of dimension n. Each element has a magnetron power source in it which radiates power through a slotted waveguide. The elements are interconnected and the radiated power comes off the array in a constant phase front.

Power is radiated at 2.45 gigahertz and collected at the platform by a dual linear rectenna. This dual linear rectenna is made up of horizontally and vertically polarized rectenna layers in the same plane. Figure 52 presents a diagram of the physical makeup of this rectenna.

Several factors affect the amount of power received at the rectenna:

- Local atmospheric meteorological conditions. The 2.45 ghz frequency was chosen because it is the operating frequency of the cooker magnetron and is virtually non-attenuated by clouds or rain.

- Off-boresight angle of the rectenna. This angle is a function of the platform flightpath and, possibly, of mission requirements.

- aircraft bank angle. This angle is a function of flight speed and turn radius. Required or maximum allowable turn radius at any given altitude may establish the off-boresight angle.

- Relative size of the rectenna compared to the size of the projected beam. Beam width is a function of the amount of focusing built into the ground antenna. This focusing ability impacts element size; the smaller the element, the greater the antenna's ability to focus its beam.

- Power distribution across the beam. Power in the beam is not constant. It is a maximum at the center and decreases toward the edges. For the types of arrays being discussed here, the beam will have a Gaussian cross-section. The majority of power transmitted may be collected between half-power points on either side of the beam.

Tapered rectennas on the wing undersurface may be considered as follows. The rectenna is of area, Srectenna, which is different from wing area, Sref., by a configuration-dependent packing factor, fpack, such that

$$\text{Srectenna} = \text{fpack} * \text{Sref.} \tag{8.4}$$

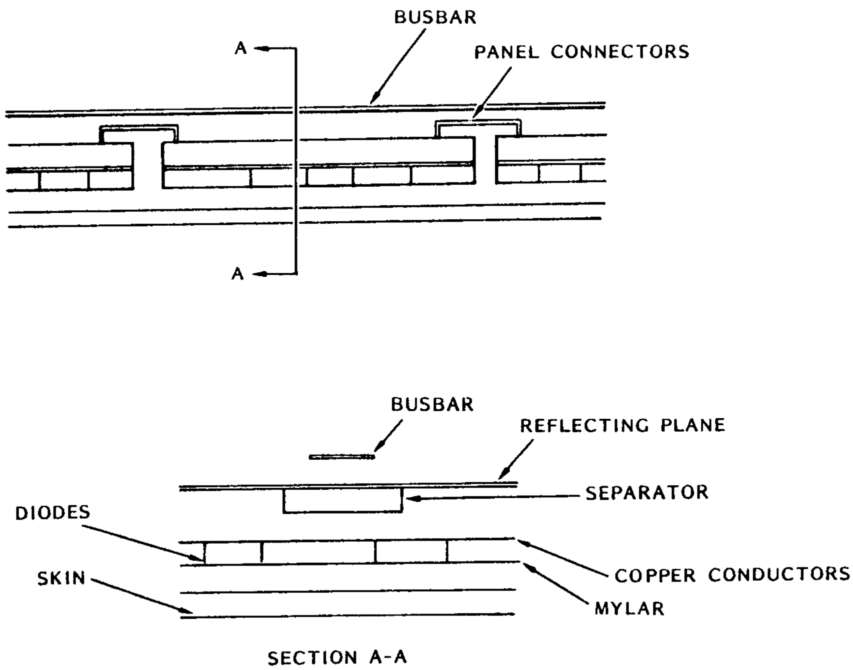


Figure 52. Makeup of a Dual Linear Rectenna

Packing factor will take into account the difference between rectenna chord and wing chord and of the portion of the wingspan which isn't covered with rectenna. This rectenna area may or may not be equal to the size of the beam being intercepted. Chances are, it won't be; but it must intercept as much of the beam's power as possible. The part of the beam which must be intercepted is the most intense portion and is found from boresight to the radius of half-power intensity. This area is called the half-power circle. Its diameter and area are,

$$Dpd/2 = 1.02 * \lambda * h/Dantenna \tag{8.5}$$

$$Apd/2 = \pi(1.02 * \lambda * h)^2/4*Dantenna^2 \tag{8.6}$$

respectively. If the rectenna is mounted on the undersurface of the wing and is roughly rectangular, then either rectenna span or rectenna chord may be limited to the diameter of the half-power circle.

If the rectenna onboard is circular, it would ideally be of the diameter and area above. This implies a circular disk underneath the platform which would add parasite area (area not producing lift) to the platform. Reference 24 analyzed this type of configuration and built a convincing case for its consideration. There's an important implication here. For any rectenna shape other than circular, the antenna shape should be very much like it to minimize power spillage. In the case of a high aspect ratio wing with a high aspect ratio rectenna, the platform will turn from being aligned with the long dimension of the ground antenna to being 90o off if the platform is flying in a closed flight path (the most likely mode of operation). This implies that spillage, the amount of the beam transmitted to the rectenna but not picked up by it, may go from manageable amounts to excessive amounts twice through a 360o turn unless the ground antenna can be turned at the same rate as the platform. If ground antenna cost is a factor in determining the feasibility of a microwave system, then this antenna turning requirement may drive cost too high, particularly if the ground antenna is very large. Not turning the antenna will also drive antenna operating cost up because power must be increased markedly twice during each 360o turn to make up for this misalignment.

Referring to Figure 53 (reproduced here from Ref. 3), the power density at the center of the rectenna when it is exactly over the center of the antenna is:

$$Pd\ rectenna = Pantenna*Aantenna*rrectenna/\lambda^2 * h^2 \tag{8.7}$$

and the power density at the center of the beam when it is offset from the center of the antenna by a turning circle of radius, rc, is

$$Pd\ rectenna = Pantenna*Aantenna*rrectenna/* \sin^2 x/x^2 * \lambda^2 * x^2$$

where $$x = \pi*1*rc/\lambda * h \tag{8.8}$$

$$Pd\ rectenna = Pantenna*Aantenna*rrectenna *(\lambda^2 * h^2) *\sin2((\pi*1*rc)/(\lambda * h))/q^2 *h^2 (\pi^2 * \ell^2 * rc^2) \tag{8.9}$$

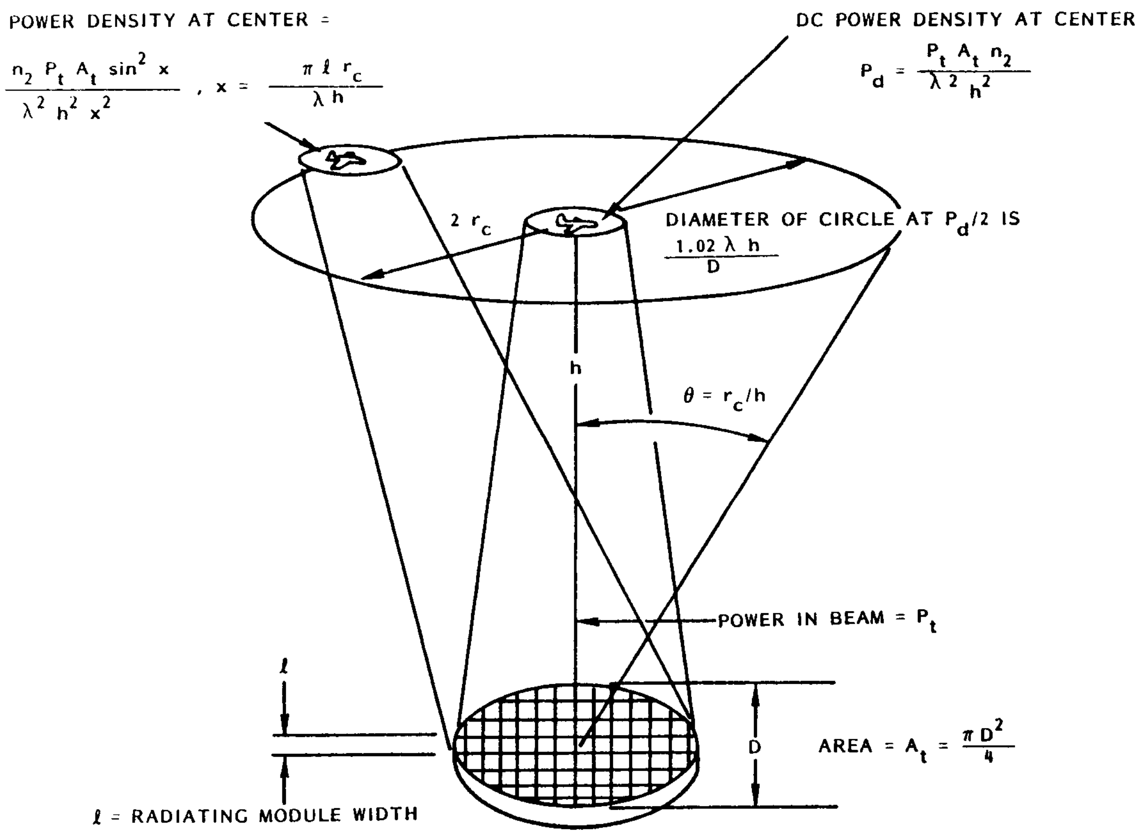


Figure 53. Effect of Altitude and off Boresight Angle on Transmittal Microwave Beam for a Flat Phased Array

$$\text{Pd rectenna} = \text{Pantenna*Aantenna* nrectenna *sin2}\ ((\pi * 1 * rc)/(\lambda * h))\ /\pi^2 * 1^2 * rc^2 \qquad (8.10)$$

Note that the area of the circle inscribed by the aircraft over the sight is rc^2. Power absorbed by the rectenna must be related to its shape and size and to the power distribution of the beam. Once this is characterized, it can be directly related to total platform power requirements made up of thrust power required, payload power and power for flight control and housekeeping functions (auxiliary power). These last two items are quite small compared to thrust power required and can usually be treated as constants at a feasibility study level of detail. Thrust power required for propulsion will be, then

$$\text{Preq}=\eta\text{prop* gearbox*}\eta\text{motor*}\eta\text{powerconditioner*}\eta\text{rectenna*}\ (\text{Prectenna-(Pauxiliary-Ppayload)*}\eta\text{powerconditioner}) \qquad (8.11)$$

Power required will also be a function of platform speed, altitude and aerodynamic parameters as well as platform power train efficiencies.

Thrust power required will be the term through which ground antenna size and platform size will be related. Equation 8.11 describes the power coming out of the rectenna and not the rectenna input power. Its required input power can be expressed as:

$$(\text{Preq})\text{in} = (\text{Preq})\text{out}/\eta\text{rectenna} \qquad (8.12)$$

This flux density, Prectenna/Srectenna, theoretically can be large, but beyond 500 to 600 watts per square meter it begins to affect rectenna mass through heat buildup in components. This upper rectenna power flux density limit may be used as a test in a parametric sizing algorithm to determine rectenna area required for a given total platform power level. Two things may happen at this point:

- Packing factor may be recalculated given an iteration on rectenna area and some configuration-dependent upper limit may be set as a parametric constraint.

- Rectenna area may be used to recalculate wing area given a configuration-dependent upper limit on packing factor. This will require iteratively resizing the entire aircraft and, perhaps, the ground antenna as well.

If circular rectennas which are not mounted on the undersurface of the wing are to be considered, then this latter method may be preferred. The rectenna area could then be related to wing area as a circle of fractional wing area and to the wing. Again, this would require resizing the entire platform and, perhaps, the ground antenna as well.

Once alternatives have been decided upon, rectenna power density, altitude and beam wavelength may be used to calculate antenna sizing parameters through equation 8.10 rewritten as

$$\text{Pantenna}*\text{Aantenna} = \text{Pd rectenna}*\pi^2*1^2*\text{rc}^2\ \eta\text{rectenna} *\sin2(\pi * 1 * \text{rc}/(\lambda * h)) \quad (8.13)$$

Power flux density at the antenna has a practical upper limit as does rectenna power density as previously discussed. For the antenna, this power flux density is a function of environmental and radio-frequency considerations on the ground. Published power density levels to date vary from 1100 watts per square meter (Ref. 16) to 400 watts per square meter (Ref. 3). The current maximum level on the ground for prolonged exposure in a commercial environment is 100 watts per square meter by regulation. If this is allowed to rise in remote areas to a level commensurate with the maximum long-term level available from commercial magnetrons, then radiated power density could be as high as 300 watts per square meter. Regardless of the level decided upon, its relationship to radiated power is presented below.

$$\text{Pantenna} = \text{Pdmax} * \text{Aantenna} \quad (8.14)$$

Equations 8.13 and 8.14 may now be combined to produce an expression for antenna area which is linked to platform design parameters:

$$\text{Aantenna}^2 = \text{Pd rectenna}*\pi^2*1^2*\text{rc}^2\ \text{rrectenna} *\text{Pdmax}*\sin2(\pi * 1 * \text{rc}/(\lambda * h)) \quad (8.15)$$

Equation 8.15 may be solved to find antenna dimensions and number of elements.

Again, two things may happen. The first relates element size to the left side of equation 8.15. The second relates platform geometry through the right side term, Pd rectenna. Elements will be square and of area 12 so antenna area will be:

$$\Delta\text{antenna} = 1^2*\text{nelements}/\text{fpack antenna}$$

where the antenna packing factor, (fpack)antenna, accounts for the difference between square elements and the non-rectangular area into which they will probably fit. Equation 8.16 then becomes:

$$(1^2 * \text{nelements}/ (\text{fpack})\text{antenna})^2 = \text{Pd rectenna}*\pi^2*1^2*\text{rc}^2/ \text{rrectenna} *\text{Pdmax}*\sin2(\pi * 1 * \text{rc}/(\lambda * h)). \quad (8.17)$$

Equation 8.17 can be manipulated further to produce an expression for the number of elements as

$$(\text{nelements}/ (\text{fpack})\text{antenna})^2 = \text{Pdrectenna}*\pi^2*\text{rc}^2/ 1^2* \text{rrectenna} *\text{Pdmax}*\sin^2(\pi * 1 * \text{rc}/(\lambda * h)) \quad (8.18)$$

$$nelements^2 = \frac{(fpack)antenna^2 * Pd\ rectenna * \lambda^2 * rc^2}{l^2 * \eta rectenna * Pdmax * sin2(\pi * l * rc/(\lambda * h))} \quad (8.19)$$

$$nelements = (fpackantenna * \pi * rc * sqroot\ of\ (Pd\ antenna/\eta\ rectenna * Pdmax))/l * sin(\pi\, l * rc/\lambda\, h)$$

Rectenna power density, Pd rectenna, required to maintain a platform in equilibrium flight can be calculated as a function of platform drag, payload power required and power required for onboard housekeeping and control functions.

If a rectenna is mounted on the wing undersurface, then rectenna area may be expressed as

$$Srectenna = croot * fpack * dpd/2 \quad (8.20)$$

$$Srectenna = croot * fpack * 1.02 * \lambda * h/Dantenna$$

Given the connection to wing root chord, an assumed wing taper ratio and a wing aspect ratio, then platform aerodynamic parameters may be calculated.

With this rectangular rectenna, its area may be limited to some configuration-dependent maximum packing factor. Wing area can be recalculated if this packing factor is exceeded. This would necessitate resizing the platform, its power requirements and, perhaps, the ground antenna.

Angular Relationships Between Antennas and Rectennas. Ref. 2 qualitatively discusses the angular relationship between a ground-based phased array in a horizontal focal plane and a planar rectenna mounted on the underside of an aircraft. Figure 54 below shows these angular relationship in an exaggerated way for ease of viewing small angles. As shown in the figure, both antenna and rectenna effective areas (areas in the beam) decrease with increases in both angles. The platform elevation angle, a, is 90o minus the rectenna off-boresight angle. The bank angle, g, is a function of turn radius, wind speed and direction and load factor. The platform is at a distance from the antenna which is a combination of its altitude and its horizontal offset. Effective transmitting area on the ground will be

$$(Aantenna)projected = A\ antenna \times \sin\theta \quad (8.23)$$

Similarly, the effective rectenna area for receiving the beam is

$$(Srectenna)projected = S\ rectenna \times \sin\theta\ \cos\phi \quad (8.24)$$

These two equations define the effective areas of antenna and rectenna and, when multiplied by appropriate power flux densities, will yield either transmitted or received power.

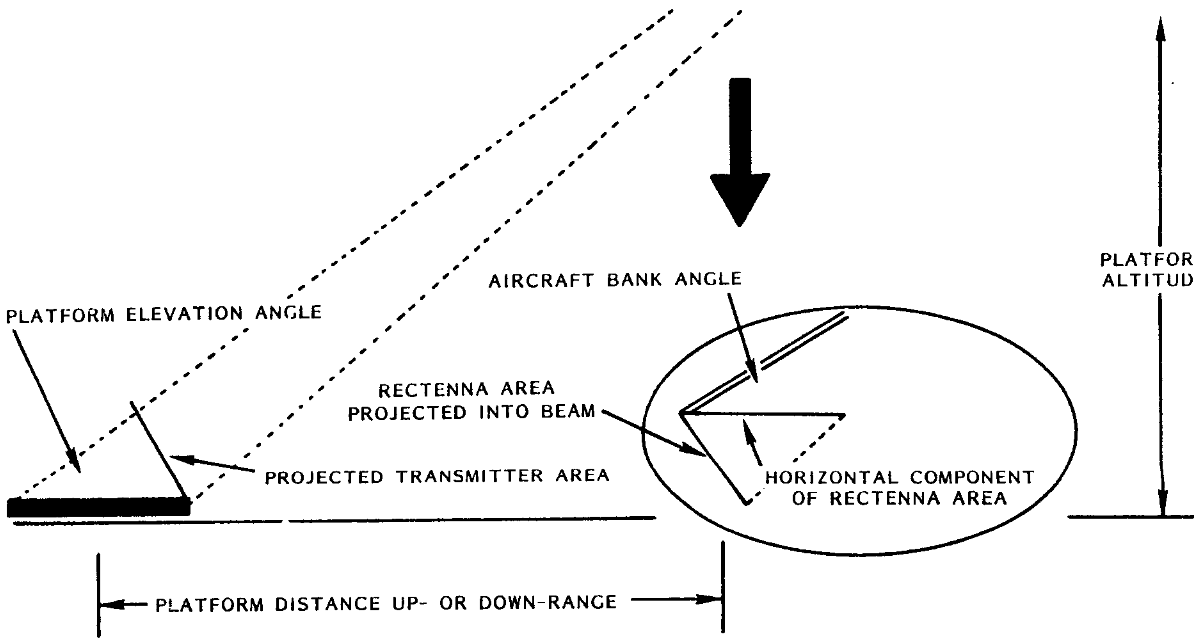


Figure 54. The Angular Relationship of Antenna and Rectenna A Microwave-Powered Aircraft

Power out of the antenna is a function of its area and of the maximum safe power flux density it can radiate, or

$$(\text{Pantenna})\ \text{radiated} = (\text{Pd max})\text{out} \times \text{A antenna} \times \sin\theta \qquad (8.25)$$

Similarly, the power received at the rectenna will be a function of the bank angle as well:

$$(\text{Prectenna})\ \text{received} = (\text{Pd max})\text{in} \times \text{S rectenna} \times \sin\theta\ \cos\phi \qquad (8.26)$$

The link between ground antenna area and airborne rectenna area can now be expressed as a function of these variables plus microwave beam wavelength, λ. The difference between radiated power and transmitted power is transmission efficiency. Ref. 2.6 presents an expression for transmission efficiency based on a transmission efficiency parameter, T, which is defined in terms of antenna and rectenna areas, wavelength and straightline distance between antenna and rectenna. The equation defining T is:

$$T=\text{sqroot (Aantenna*Srectenna)/ *sqroot}(\lambda^2 + r^2)) \qquad (8.27)$$

The relationship between T and transmission efficiency was presented in Figure 51 which is from the same reference. The area of interest on this curve is the linear portion which can be approximated with a straight line through the origin and a point at (0.65,1.00). Transmission efficiency can then be conveniently expressed as:

$$\eta\text{transmission}= 0.65\ T \pm 0 \qquad (8.28)$$

A transmission efficiency of less than 1.00 effectively reduces the power density received at the rectenna, or

$$(\text{Pd max})\ \text{in}= \eta\text{transmission*(Pd max) out} \qquad (8.29)$$

Equation 8.25 can be rewritten as

$$(\text{Pdmax})\text{out} = \text{Pantenna/(Aantenna*}\sin\theta\ ) \qquad (8.30)$$

and inserted into equation 8.26 along with transmission efficiency to relate power generated at the antenna to power received at the rectenna. This expression can be expanded to incorporate equations 8.27 and 8.28 and terms can be collected to produce the expression which was used in this parametric sizing methodology:

$$\text{Prectenna=Pantenna*}\eta\text{transmission*Srectenna*Cos}\theta\text{/Aantenna} \qquad (8.31)$$

$$\text{Prectenna=0.65*Pantenna*Srectenna}^{3/2}\text{*Cos}\theta/\lambda \times \text{sqroot(Aantenna}(h^2 + rc^2)) \qquad (8.32)$$

Dish Equations

Power density at the antenna array, which is made up of carefully spaced individual dishes, is a function of antenna size, wavelength and distance over which power is transmitted. Antenna gain is defined as the ratio of directionally transmitted power to the power level radiated spherically, or

$$\text{Gain} = \text{directional power/spherical power} \tag{8.33}$$

$$\text{Gain} = 4\pi \text{Aantenna}/\lambda^2 \tag{8.34}$$

Gain is multiplied by antenna output power and divided by area to produce transmitted power flux density as

$$\text{Pd antenna} = \text{PantennaGain}/4\pi R^2 \tag{8.35}$$

$$\text{Pd antenna} = 4 \times \text{PantennaDantenna}^2\ /4\pi\lambda 2R^2 \tag{8.36}$$

$$\text{Pd antenna} = \text{PantennaDantenna}^2\ /\lambda 2R^2 \tag{8.37}$$

$$\text{Pd antenna} = \text{Pantenna}(\text{Dantenna}/\lambda R)^2 \tag{8.38}$$

If the beam is focused in the near-field, its diameter at the focusing altitude will be:

$$\text{Dbeam} = R\ /\text{Dantenna} \tag{8.39}$$

Similarly, the corresponding power distribution will be

$$\text{Beam Shape} = [(\sin x)/x]^2 \tag{8.40}$$

A rectenna power density equation exists for dish arrays which is similar to the equation previously written for flat arrays. One additional variable is added which is a subarray steering angle, al. The equation is

$$(\text{Pdensity})\text{rectenna} = E*\text{PantennaAeff}\cos 2\theta * \sin 2(Y)\sin 2(Y/N)/ Y^2 * Y^2/\text{ndishes} \tag{8.41}$$

Equation 8.38 can be expanded by writing expressions for antenna power and antenna area:

$$\text{Pantenna} = (\text{Pdmax})\text{antenna}*\text{Aantenna} \tag{8.42}$$

$$\text{Aantenna} = \text{Adish}*\text{ndish}/(\text{fpack})\text{antenna} \tag{8.43}$$

With these substitutions, equation 8.42 becomes:

$$\text{Pdrectenna} = [(0.85\pi\text{dish}^2\text{ndishes}^3\text{LIFF}(\text{Pdmax})\text{antenna}) /(Y^4(\text{fpack})\text{antenna})] *(\cos Y)(\cos 2\theta)(\sin 2Y)[\sin 2(Y\sqrt{\text{ndishes}}) \tag{8.44}$$

Dish area can be rewritten in terms of its diameter and substituted into equation 8.44 to yield:

$$\text{Pdrectenna}=[(0.85\pi^4 \text{Ddish}^4 \text{ndishes}^3 \text{LIFF(Pdmax)antenna})/(16\pi^2 Y^4 (\text{fpack}) \text{antenna})]*(\cos Y)(\cos 2\theta)(\sin 2Y)[\sin 2(Y\sqrt{n}\text{dishes})] \quad (8.45)$$

Next, Y^4 can be written as

$$(\theta l/\lambda)^4 = (Y/\pi \text{Ddish})^4 \quad (8.46)$$

and this expression may be substituted into equation 8.45 to yield:

$$\text{Pdrectenna}=[(0.85\pi^4 \text{ndishes}^3 \text{LIFF(Pdmax)antenna})/(16\pi^2 \ l^4 (\text{fpack}) \text{antenna})] *(\cos Y)(\cos 2\theta)(\sin 2Y)[\sin 2(Y\sqrt{n}\text{dishes})] \quad (8.47)$$

Equation 8.47 above is the expression which was used in the ground subsystem sizing methodology for estimation of antenna parameters given a required value of rectenna power flux density.

This power flux density at the rectenna is the result of focusing the microwave beam in the near-field. The corresponding half-power beam width will be:

$$\text{Dbeam}= 0.44*\text{ro}*\lambda/\text{Dantenna} \quad (8.48)$$

Detailed Considerations

Given a typical slotted waveguide array of 39 x 78 meters, it can be shown that a microwave-powered platform will be in the radiating near-field, or Fresnel zone, of the antenna as shown by:

$$0.627(\text{Dantenna}^3/\lambda)^{1/2} \leq R \leq 2\text{Dantenna}^2/\lambda \quad (8.49)$$

This puts R in the range of 1223 to 99 763 meters (4000 to 327,000 feet). R is the straight line distance between the antenna and the rectenna.

In the Fresnel zone, there is a net flow of power being transmitted; however, there is also an associated reactive field (stored energy). In the far-field, the reactive field diminishes to zero and the region is dominated by purely real power. Power flux density is a function of the field strengths of both the energy field and the reactive field. The equation which can be used to calculate power density in the near-field beam is

$$\text{Wave}= \text{Re}[E \times H] \quad (8.50)$$

In the far-field, closed form expressions can be easily found for power density, as shown in preceding sections. In the Fresnel zone, however, closed form expressions are difficult to derive due to the addition of higher order terms used to describe the E and H fields. In general, power flux density will be less in the Fresnel zone. Figures 55 and 56 show computed E-plane and H-plane antenna patterns for an 8 x 8 slot radiating element in a flat array. A large array antenna pattern is formed by using the following relationship:

$$\text{Array pattern} = \text{Element pattern} \times \text{Array factor} \tag{8.51}$$

Where Array factor is the large array antenna pattern using isotropic elements. The computed E-plane and H-plane antenna pattern for a 39 x 78 meter array is shown in Figures 57 and 58. The main beam for the large array is quite narrow and scanning of the beam will be limited to the half-power beam width of its 8 x 8 radiating elements. Notice also that the grating lobes appearing in the large array antenna pattern are due to the large spacing between radiating elements. This will also be the case with a dish array; however, grating lobe levels will be determined by the antenna pattern of the dish elements.

Focusing of the beam will be accomplished by appropriate phase distribution across the array. Digital phase shifters provide discrete phase shifts and introduce quantitization phase errors which can make focusing and beam steering difficult. The dish array offers the advantages of being able to focus on the platform by mechanically aiming the individual antennas and allowing wider scan angles without significant reduction in power density at the platform.

8.3 Subsystem Interactions

Payload Interaction with Platform and Ground Antenna

Payload factors affecting system ability to take continuous in-situ measurements for long durations are payload mass, drag producing payload attachment features such as viewing ports or fairings, and odd viewing angles for calibration. Features which create drag result from the need for instrument ports in the platform skin or bulges to hide unsightly lumps and corners. Viewing ports are required to ensure that the platform provides those interfaces required to achieve the second mission goal of observation. Required viewing ports will depend on the particular observation. NADIR viewing instruments and scanners looking through NADIR will require a clear view of earth. Limb viewing instruments will require a clear view of the earth's limb. Some limb scanners must observe the sun as it rises and sets and, hence, may determine platform flightpath during part of each day's mission. Solar viewing instruments must be able to continuously track the sun. Most instruments will frequently need to be calibrated by viewing either the sun and/or deep space. Platform structure must be excluded from the viewing envelope in all cases. To summarize, viewing requirements will be:

- Placement of payload instruments on the platform in accordance with the viewing requirements of each payload instrument;

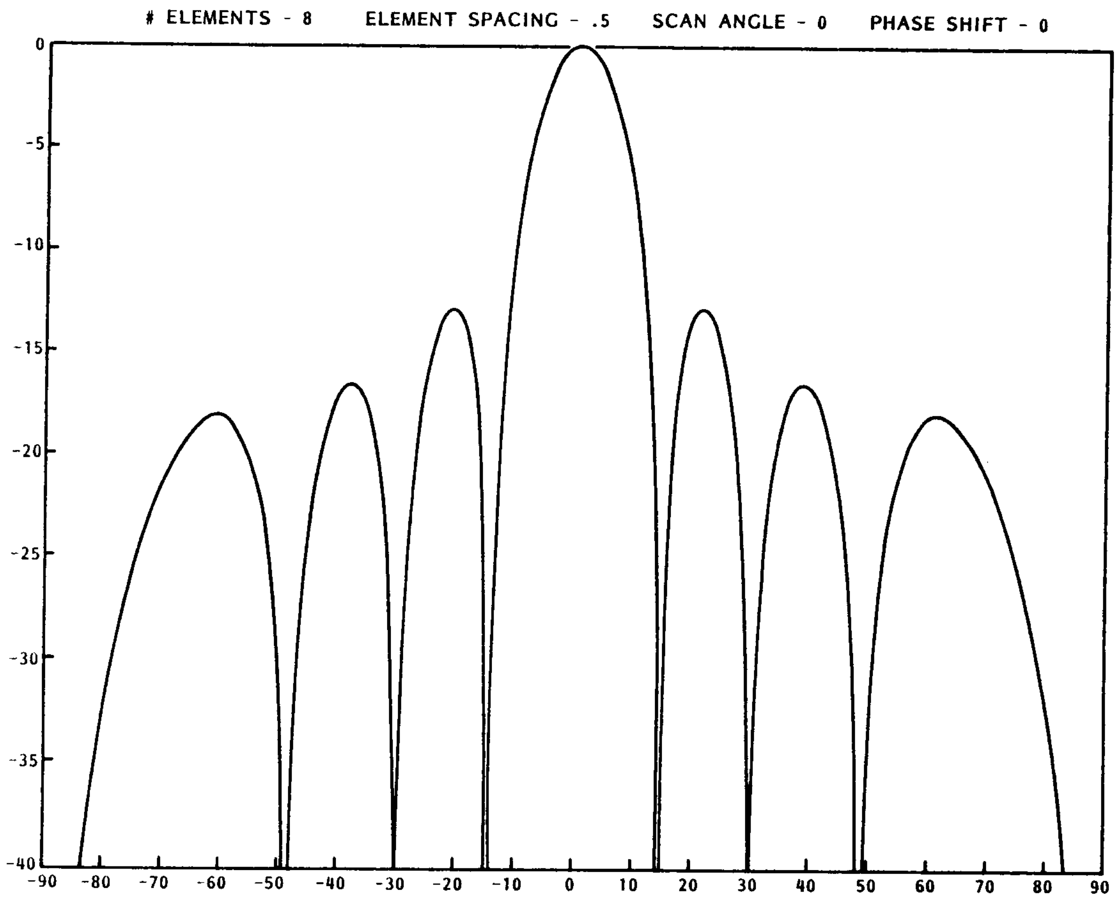


Figure 55. Computed E-Plane Antenna Pattern for an 8 x 8 Slot Radiating Element in a Flat Array

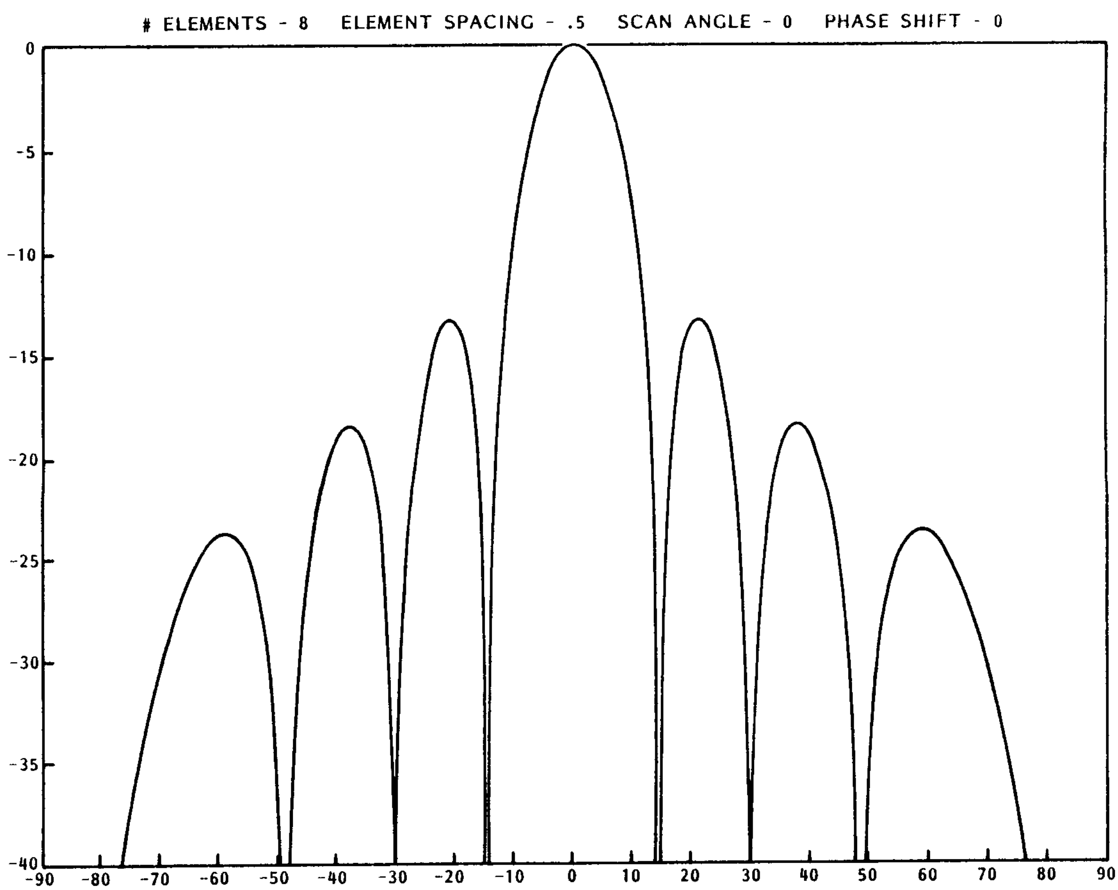


Figure 56. Computed H-Plane Antenna Pattern for an 8 x 8 Slot Radiating Element in a Flat Array

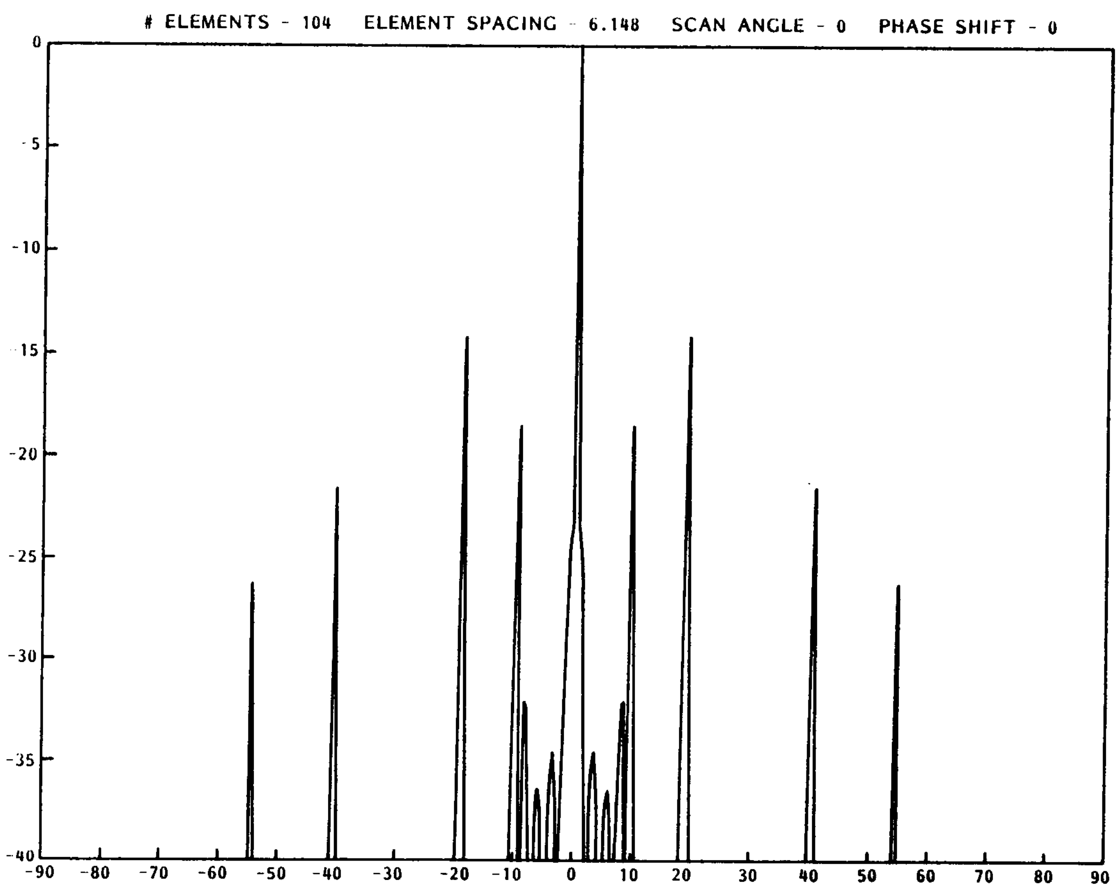


Figure 57. Computed E-Plane Antenna Pattern for a 39 x 78 Meter Array

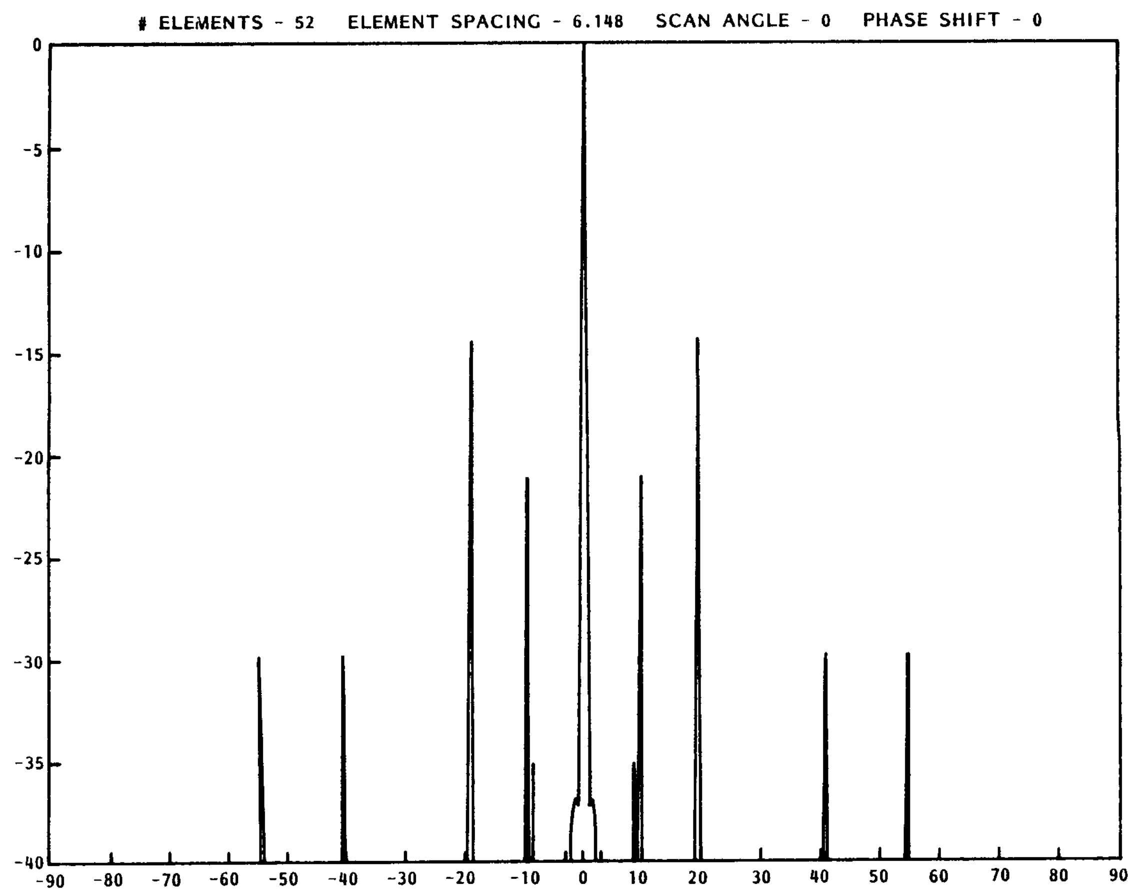


Figure 58. Computer H-Plane Antenna Pattern for a 39 x 78 Meter Array

- Careful coordination between the payload observation timeline and the operational timeline flightplan of the platform.

Payload viewing requirements may dictate modifications to the instruments, although such modifications could be costly and should be kept to a minimum.

To successfully make the required observations, payload contamination must be rigorously controlled. The necessity for contamination control will place requirements on the design and operation of the platform. Special protection of the payload will be required during all phases of the mission including preflight, climb to altitude, daily operations and during descent and recovery.

Instruments having components at cryogenic temperatures will require special attention to preclude icing up. Certain infrared instruments require cooled detectors to achieve low-noise measurements. Passive cooling using a radiative cooler is typical and the cooler is designed to couple the detector to cold deep space. The efficacy of a radiative cooler operating in the stratosphere requires further study. It may not be able to achieve sufficiently low temperatures due to earthshine scattering off the residual atmosphere at altitude, emission from the residual atmosphere and contamination buildup from both the atmosphere and the platform. In addition, warm windows would be required over the detector and over the radiative cooler inner stage to prevent contamination buildup. At a minimum, the detector window will require refocus of the payload optics system. The window may require further redesign of the instrument and may adversely affect radiometric performance. The radiative cooler inner stage window, if needed, may adversely affect the ability of the cooler to radiatively cool the detectors. Hence, other means may be necessary. Alternatives might be passive stored cryogen or an active refrigeration system.

Since the platform is bathed in microwave radiation, the instruments must operate in this environment. This may require shielding of instruments and cables.

Ground Antenna Interaction with Platform

One of the major system cost drivers is the interaction of the diameter of the focused microwave power beam, or spot, relative to rectenna and platform geometries. At a nominal altitude of 20 km (65 600 feet), the microwave power spot varies from about 10 to 40 m (33 to 132 feet) in diameter. Power density, measured in watts per square meter, is the greatest at the center of this spot and decreases roughly logarithmically toward the edges. Useful power is usually considered to exist between the center and a radius established at the points where power has decreased to one-half the value at the center of the spot. This smaller circle is known as the half-power circle and should ideally correspond to the diameter of the platform's rectenna. If the rectenna is a disk, then its diameter is limited to this value. There is a corresponding ground antenna diameter to produce the required spot size for every ground power option.

There are a wide variety of platform subsystem shapes to carry the rectenna. These shapes may vary from a circular wing of just more than aspect ratio 1 and slightly larger than the half-power circle in diameter to a very efficient sailplane wing of very high aspect ratio. The highly efficient aerodynamic shape will require less power than a less efficient shape but will intercept less of a circular spot. Because less is intercepted by a highly efficient sailplane type wing, more power must be beamed up and more must be generated on the ground requiring a larger array. The tradeoff to be performed, then, is between highly efficient subsystems aloft and on the ground and less efficient subsystems optimized to work together to minimize total system cost. Platform subsystem configuration and ground subsystem options change the details of this trade, but not the basic logic.

8.4 System Optimization

System Considerations and Trade-offs

The systems engineering approach employed during this pre-Phase A feasibility study has been to develop a system sizing methodology sensitive enough that a wide variety of design parameters may be examined to determine their effect on total system cost. Figure 59 depicts several categories of tradeoffs which must be made to arrive at feasible and well-balanced systems. Parameters are divided into three categories indicating the emphasis placed on them during the study. The first category includes items of highest priority to determining system feasibility.

Payload subsystem observational data requirements (ODRs) determined the payload complement of the CO-OPS platform and established definite platform and data subsystem performance parameters. Viewing requirements and payload sensitivity to a microwave environment constrained platform geometry. Contamination, cooling, power required and mass affected platform power train size and total system power required.

Parametric Trade-Offs

Figure 60 presents the ranges of design parameters examined during this study. The first column shows the number of possible combinations of parameters, many of which are incompatible. The second column shows the number of cases actually examined using this microwave system sizing methodology. Wide ranges of ground and platform design variables were considered in order to uncover any possible unique solutions outside the expected ranges.

SYSTEM CONSIDERATIONS AND TRADEOFFS			
PAYLOAD SUBSYSTEM	PLATFORM SUBSYSTEM	GROUND SUBSYSTEM	DATA SUBSYSTEM
● SENSORS	● PAYLOAD CONSTRAINTS	● DISH ARRAYS	● DATA RATES
● ODR'S OBSERVATIONAL DATA REQUIREMENTS	● RECTENNA AREA	● FLAT ARRAYS	● FLIGHT PATH
● VIEWING REQUIREMENTS	● WINDS ALOFT	● DOWNRANGE TRANSMISSION	● DATA INTERFACE REQUIREMENTS
● CONTAMINATION	● LIFE CYCLE COSTS	● POINTING/ TRACKING	● LIFE CYCLE COSTS
● COOLING	● SUBSYSTEM INTEGRATION	● LIFE CYCLE COSTS	● DATA STORAGE
● MICROWAVE ENVIRONMENT	● STRUCTURE	● MAINTAINABILITY	● DATA REDUCTION
● PLATFORM INTERFACE	● LAUNCH/RECOVERY	● SITE WEATHER	● POWER REQUIRED
● POWER REQUIRED	RELIABILITY	● SITE PREPARATION	● THROUGHPUT
● WEIGHT	● EMERGENCY POWER	● MOBILITY	● DOWN LINK
● LIFE CYCLE COSTS	● MOBILITY	● ENVIRONMENT	● PLATFORM/GROUND STORAGE

Figure 59. System Considerations and Tradeoffs

PARAMETRIC TRADEOFFS			
RANGES EXAMINED		POSSIBLE COMBINATIONS	CASES ACTUALLY RUN
PLATFORM			
ASPECT RATIO	1 - 40	35	35
WINGSPAN	5 - 120M (16 - 394 FT)	21	21
AIRSPEED	20 - 200 MPS (39 - 389 KTS)	9	9
ALTITUDE	6 - 40 KM (19,680 - 131,200 FT))	6	6
PAYLOAD			
MASS	227 - 560 KG (500 - 1500 LB_f)	4	1
POWER REQUIRED	150 - 1500 WATTS	3	1
GROUND ANTENNA			
TYPE	FLAT ARRAYS, DISHES, SOLID STATE	3	3
TRANSMITTER	MAGNETRONS, KLYSTRONS	2	2
		~ 20 MILLION	240,000

Figure 60. Ranges of Design VAriables Examined During the CO-OPS.

Trade-off Considerations

As described in the platform subsystem section, platform costing has been estimated using variations of accepted industry practices and coefficients have been changed to reflect the high-altitude low speed domain in which the CO-OP System will operate. This approach has correlated well with previous solar HAPP work (Ref. 12). The result is a method of providing first system RDT&E costs which should accurately indicate trends and show the major system cost drivers.

As an example of a platform parameter which is a major system cost driver, Figure 61, shows the sensitivity of first system RDT&E cost to platform operating altitude. The range examined is from 4 to 40 km (13 to 131 kfeet). Note that first system RDT&E cost reaches a minimum at altitudes of 18 to 24 km (59 to 79 kfeet). This will be the operating range of CO-OPS.

Trade-Off Procedure

The trade-off procedure developed for this system sizing methodology uses first system RDT&E cost as a figure of merit for choosing the most promising CO-OP Systems for further analysis. Early iterations determined possible subsystem combinations as previously mentioned and described each in terms of common design parameters such as component peak power-to-mass ratio and related efficiency at that point. Also characterized was subsystem cost as a function of common design variables. The platform subsystem cost equations were presented in the platform subsystem section and the ground subsystem cost equations were presented in the ground subsystem section.

The subsystem costing procedures were linked through design parameter values established in the system sizing equations given earlier in this section. Once each component of the system has been sized and its related cost estimated, results may be presented in a uniform format. The series of plots which resulted from initial runs with different combinations of cases created plots could be used to determine platform and ground subsystem design values and first system RDT&E costs. Variations were then be run to determine the effect of altitude and payload mass and power on total first system RDT&E cost.

The first set of cases run paired up ground subsystem and platform subsystem alternatives:

- o Flat slotted ground array with a disk rectenna (System Type 1);
- o Flat slotted ground array with a wing-mounted rectenna (System Type 2);
- o solid-state ground array with a disk rectenna (System Type 3);
- o solid-state ground array with a wing-mounted rectenna (System Type 4);

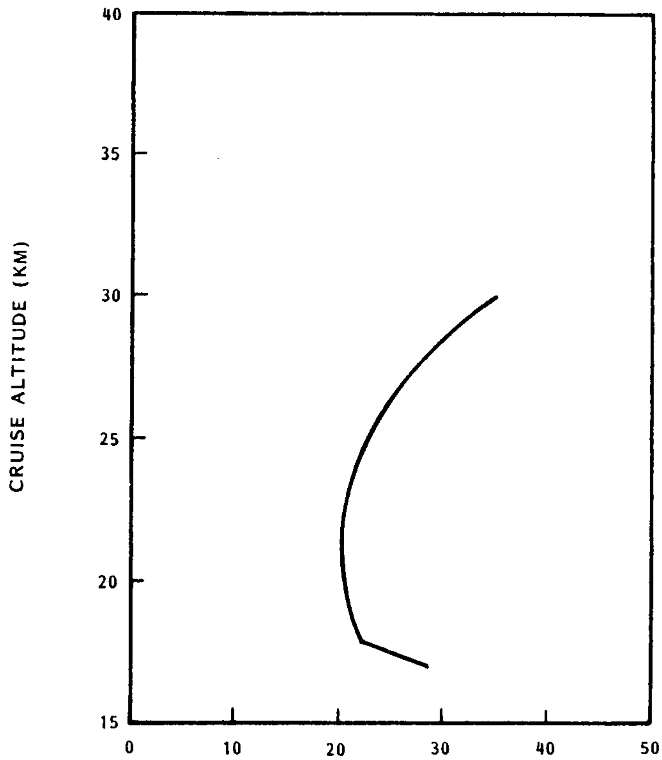


Figure 61. First System RDT&E Cost Vs. Platform Cruise Altitude for a Platform with a Disk Rectenna and a Flat Slotted Array

- 11 meter dish ground array with a disk rectenna (System Type 5);
- 11 meter dish ground array with a wing-mounted rectenna (System Type 6);
- 4.5 meter dish ground array with a disk rectenna (System Type 7);
- 4.5 meter dish ground array with a wing mounted rectenna (System Type 8);
- Slotted ground arrays on pedestals with a disk rectenna (System Type 9); and
- Slotted ground arrays on pedestals with a wing-mounted rectenna (System Type 10).

Results were presented as plots of platform cruise altitude versus first system RDT&E cost and determine if a cruise altitude existed at which system cost was a minimum. A more detailed dump of the same data was then used to determine platform and ground subsystem sizes.

Constraints applied included platform design limitations such as upper and lower limits on wingspan and aspect ratio, lift coefficient and airspeed. The ground subsystem was limited to a range of array areas and array output power flux density was limited to roughly 300 watts per square meter. Power flux density at the rectenna was also limited to 600 watts per square meter.

Parametric Approach

The preceding pages developed sizing equations for both a ground antenna and an airborne rectenna. These equations may be used to produce parametric plots showing potentially feasible microwave-powered platform and associated ground antennas. One of these plots will be developed here, but first it is necessary to discuss the parameters which will be used to present results.

The equations shown earlier may be used along with geometrical relationships to create sizing algorithms which calculate parametric platforms by varying aspect ratio and wingspan. For a given set of initial conditions--altitude, airspeed, payload mass, payload power--aspect ratio may be varied for one value of wingspan to produce the curve shown in Figure 62.

This may be repeated, then, for several values of wingspan and the following plot created.

Once lines of equal aspect ratio are connected, system or subsystem design constraints may be applied. The result is shown below in Figure 64. Constraints may be in the form of aerodynamic limits (platform lift

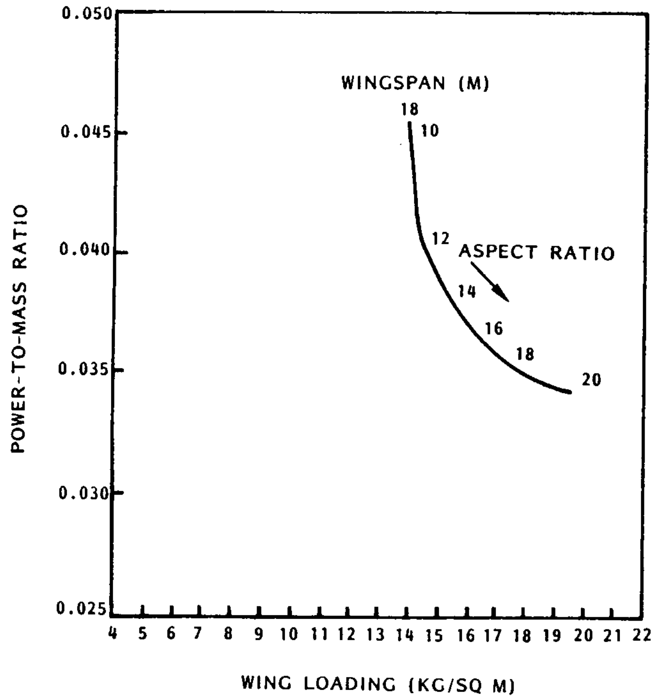


Figure 62. Sample Plot of the Effect of Aspect Ratio on Power-to-Mass Ratio and Wing Loading for a Microwave Hale RPV

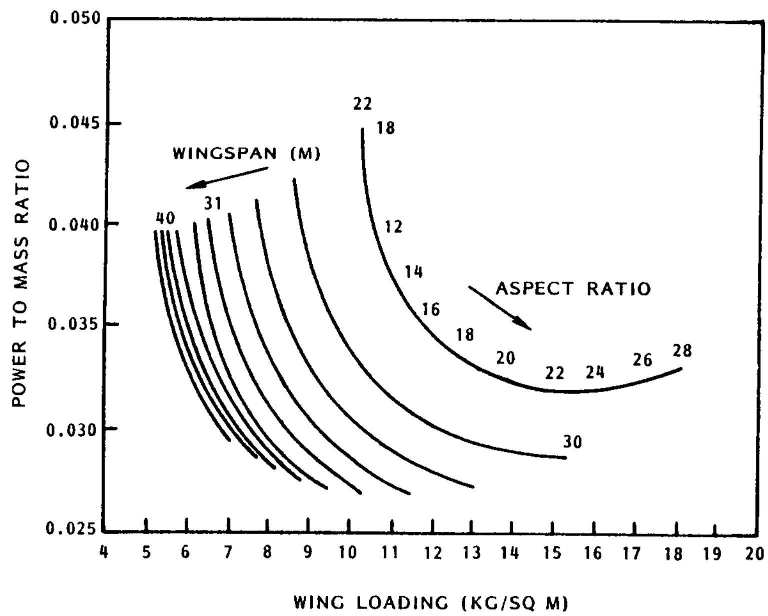


Figure 63. The Effect of Aspect Ratio Variations on Power-to-Mass Ratio and Wing Loading for Several Wingspans for a Microwave Hale RPV

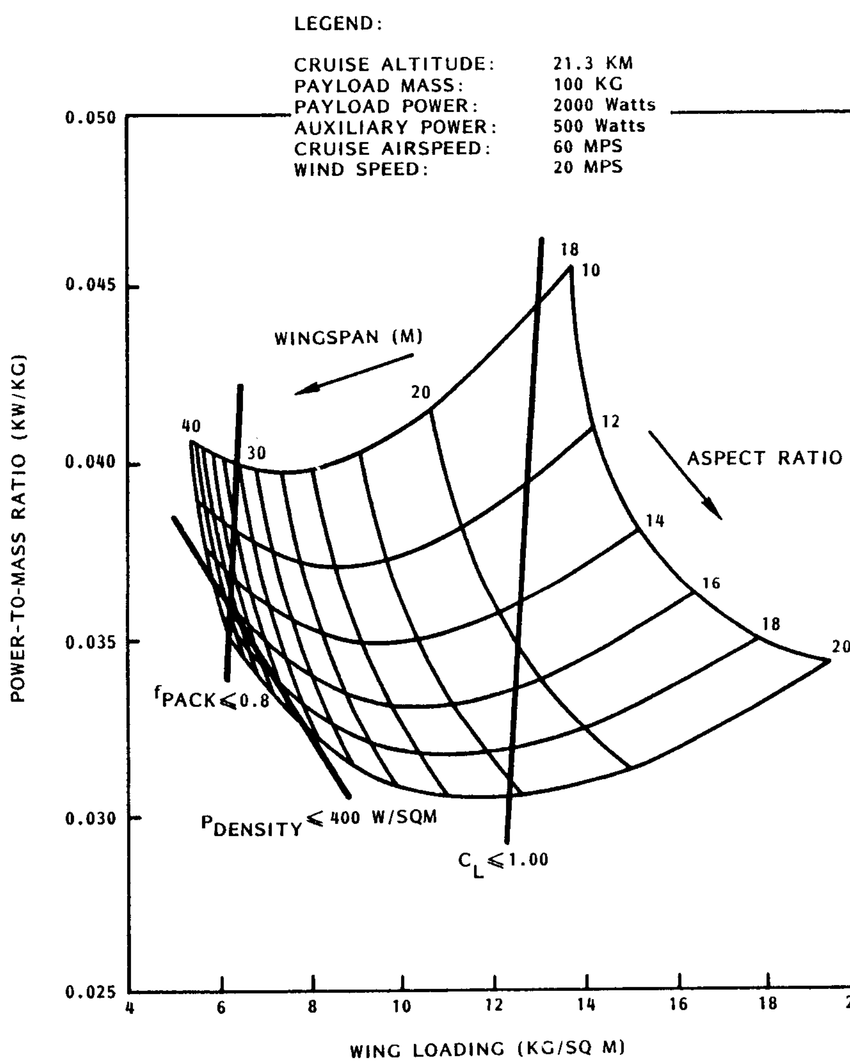


Figure 64. Parametric Plot of Microwave Hale RPV Showing Constraint Lines

coefficient), geometric limits (rectenna packing factor), or power limits (rectenna input power flux density). These constraints define the area of this plot where feasible CO-OPS platforms may be found. By examining many of these plots representing variations of basic parameters, the minimum cost platform is found.

The methodology also examines similar ground subsystem design parameters and matches these with platforms to arrive at minimum cost system combinations.

8.5 Study Technical Results

The following plots present system sizing data for each of the ten subsystem combinations described earlier. The payload subsystem used for each remained constant at a mass of 270 kg (595 lbf) and a power of 500 watts. Although the recommended prototype payload power was 185 watts, 500 was used to provide margin for additional onboard busing and synergistic control of payload components. The effect of variations of payload from 0 to 1000 watts produced very minor variations in system costs, well within the error band of these study results. The effects of variations in payload mass, however, produced markedly different results in some cases. These variations will be discussed in a later subsection.

Flat Slotted Ground Arrays

Two plots are shown below which summarize the effect of changes in altitude on first system RDT&E cost for flat slotted ground arrays. The upper curve is for a system using a disk rectenna and the lower curve is for a system using a wing rectenna. Note that both systems tend to prefer platforms which cruise at 20 km (65 600 feet).

Each combination of subsystems defined a minimum cost system with its attendant design parameters. These are listed in Table 38.

The following charts present the trends in first system RDT&E cost to be expected as both payload mass and altitude vary over the range of interest. Winds aloft govern the selection of platform cruise speed and, hence, the cheapest CO-OP Systems are in the minimum wind region. Note that the platform cruise altitude for minimum cost increases with payload mass from 21 km (70 000 feet) at 227 kg (500 lbf) to 22 km (72 160 feet) at 680 kg (1500 lbf) for a flat slotted ground array combined with a disk rectenna on the platform.

8.6 Integrated System Description

Overall System Performance

The CO-OP Systems just described analytically will fulfill the primary mission carrying the recommended payload weighing 270 kg and using 185

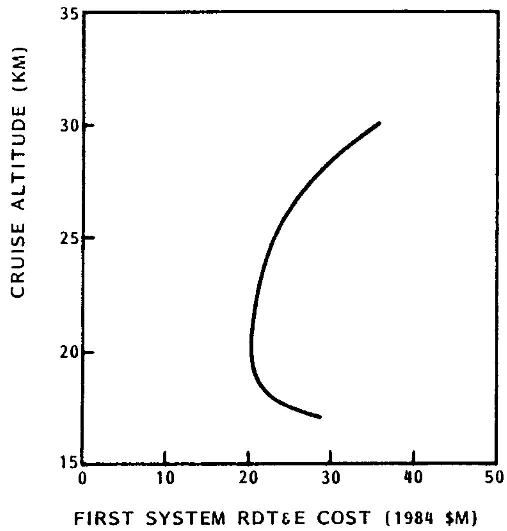


Figure 65A. Effect of Altitude Variations on First System RDT&E Cost for a Flat Slotted Array and a Disk Rectenna

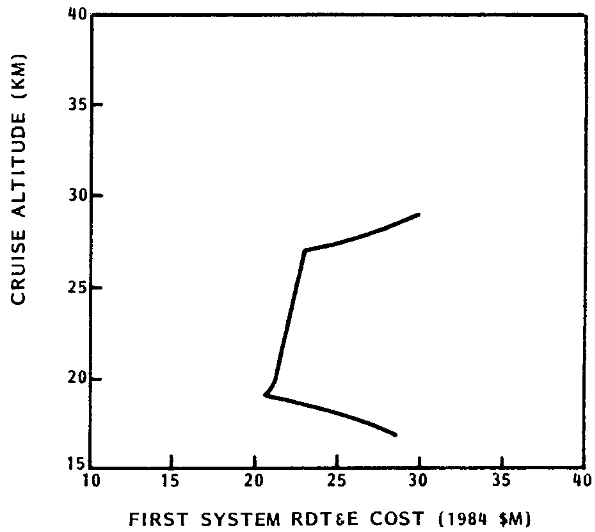


Figure 65B. Effect of Altitude Variations on First System RDT&E Cost for a Flat Slotted Array and a Wing Rectenna

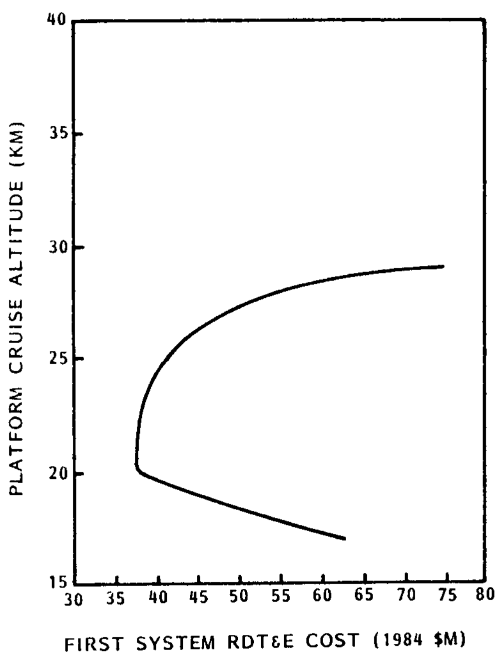


Figure 66A. Effect of Altitude Variations on First System RDT&E Cost for a Solid State Array and a Disk Rectenna

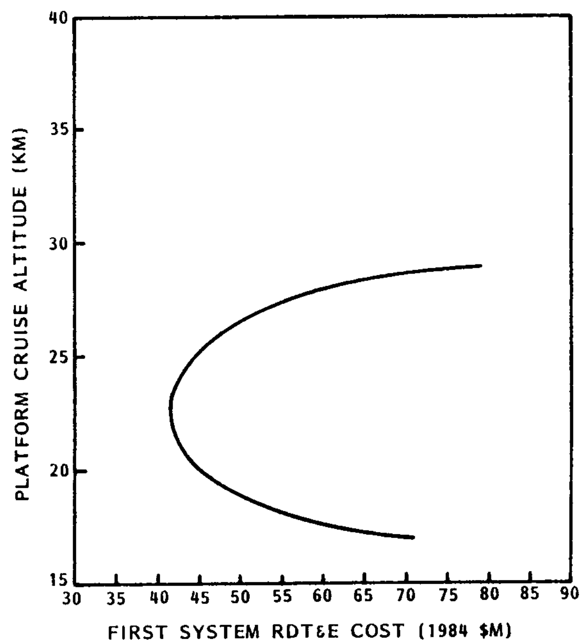


Figure 66B. Effect of Altitude Variations on First System RDT&E Cost for a Solid State Array and a Wing Rectenna

TABLE 38. OPTIMUM CO-OP SYSTEMS FOR MAJOR SUBSYSTEM ALTERNATIVES

SYSTEM TYPE	ALTI-TUDE KM	AIR-SPEED MPS	SPAN M	PLATFORM AR	PLATFORM TOGM KG	S_{REF} SQM	L/D	S_{RECT} SQM	PFD W/SQM	GROUND AREA SQM	GROUND POWER MW	TOTAL COST $M
1	20	50	44	21	778	92.	29	55	450.	3025	2.5	20.8
2	19	50	42	14	821	126.	24	76	405.	3025	2.5	21.0
3	20	50	50	22	858	114.	29	68	401.	8100	0.9	37.2
4	20	50	40	13	806	123.	24	74	406.	7225	1.4	41.8
5	20	50	40	19	755	84.	28	53	493.	7238	1.3	35.4
6	19	50	34	14	698	83.	25	50	510.	7238	1.3	34.8
7	20	50	48	21	842	110.	28	66	412.	6082	1.1	29.5
8	20	50	36	16	683	81.	26	49	488.	6793	1.2	30.2
9	19	50	50	22	872	114.	28	68	419.	4072	1.2	24.6
10	19	50	40	14	785	114.	25	69	424.	4072	1.2	23.5

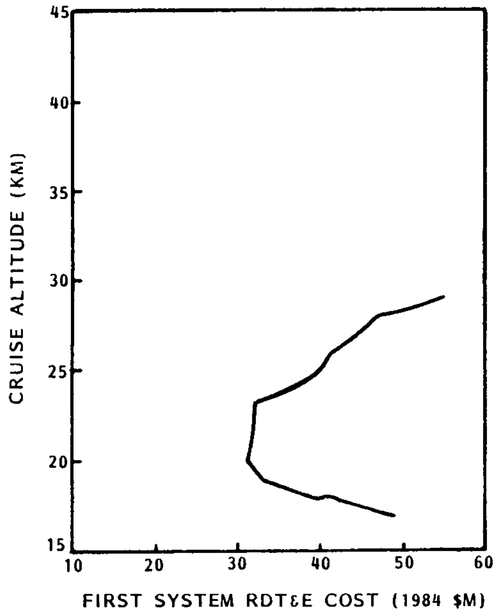


Figure 67A. Effect of Altitude Variations on First System RDT&E Cost for an 11 Meter Dish Array and a Disk Rectenna

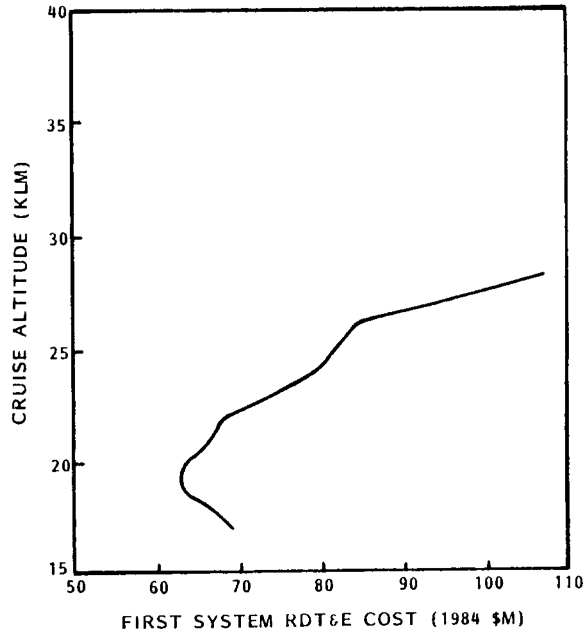


Figure 67B. Effect of Altitude Variations on First System RDT&E Cost for an 11 Meter Dish Array and a Wing Rectenna

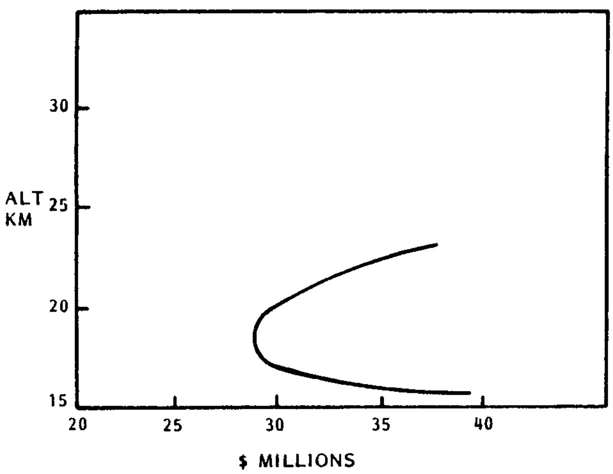


Figure 68A. Effect of Altitude Variations on First System RDT&E Cost for a 4a.5 Meter Dish Array and a Disk Rectenna

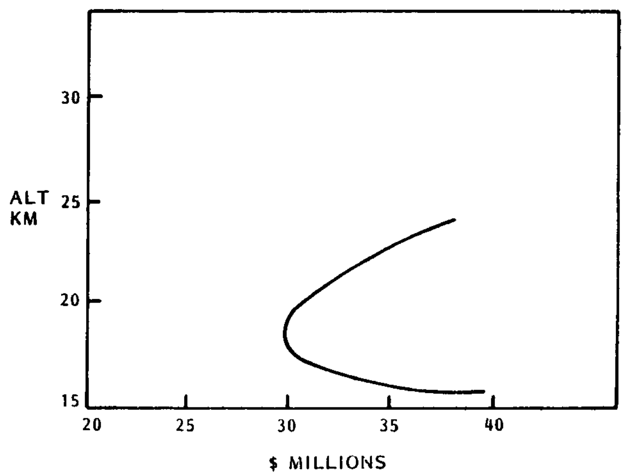


Figure 68B. Effect of Altitude Variations on First System RDT&E Cost for a 4.5 Meter Dish Array and a Wing Rectenna

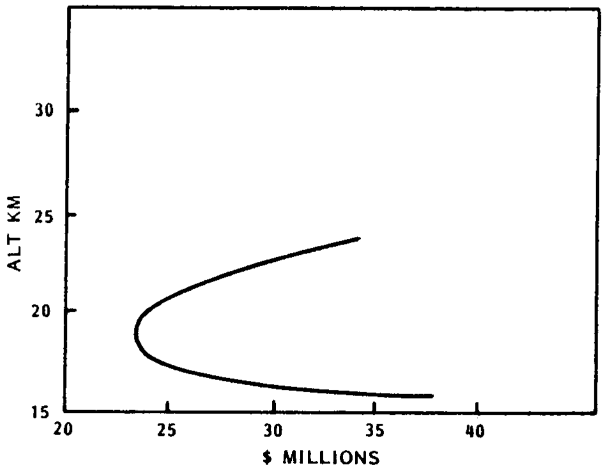


Figure 69A. Effect of Altitude Variations on First System RDT&E Cost for a Slotted Array on Pedestals and a Disk Rectenna

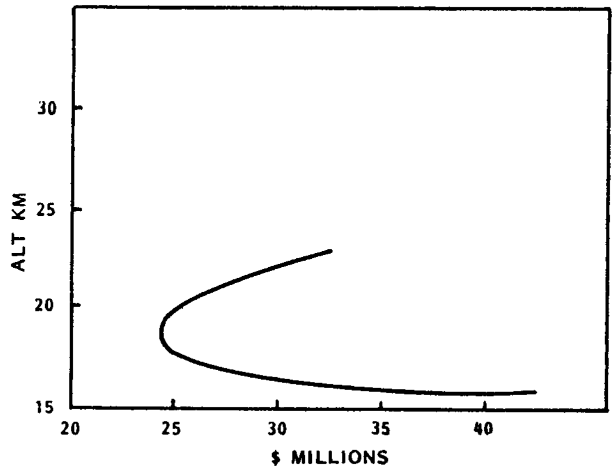


Figure 69B. Effect of Altitude Variations on First System RDT&E Cost for a Slotted Array on Pedestals and a Wing Rectenna

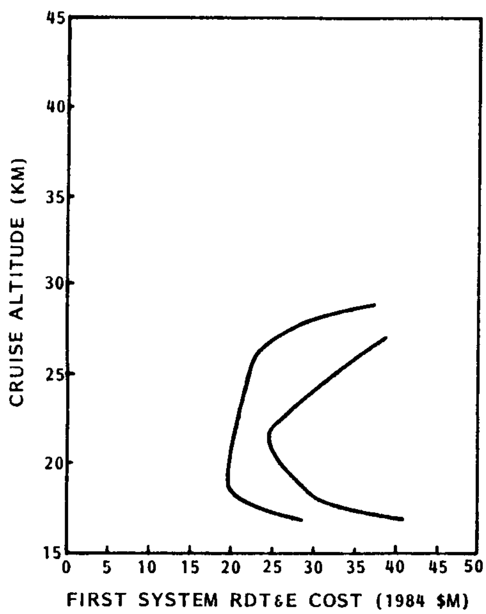


Figure 70A. Effect of Altitude Variations on First System RDT&E Cost for a Flat Slotted Array and a Disk Rectenna

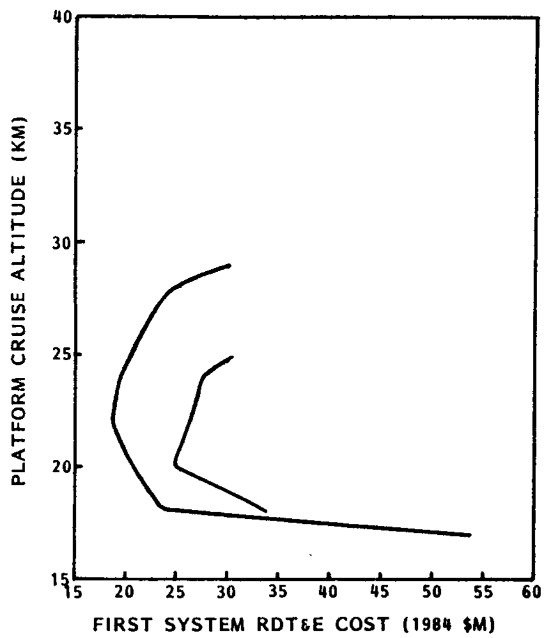


Figure 70B. Effect of Altitude Variations on First System RDT&E Cost for a Flat Slotted Array and a Wing Rectenna

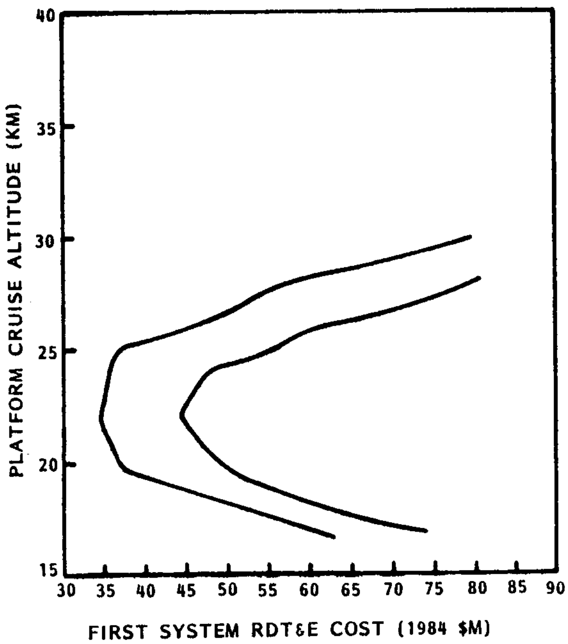


Figure 71A. Effect of Altitude Variations on First System RDT&E Cost for a Solid State Array and a Disk Rectenna

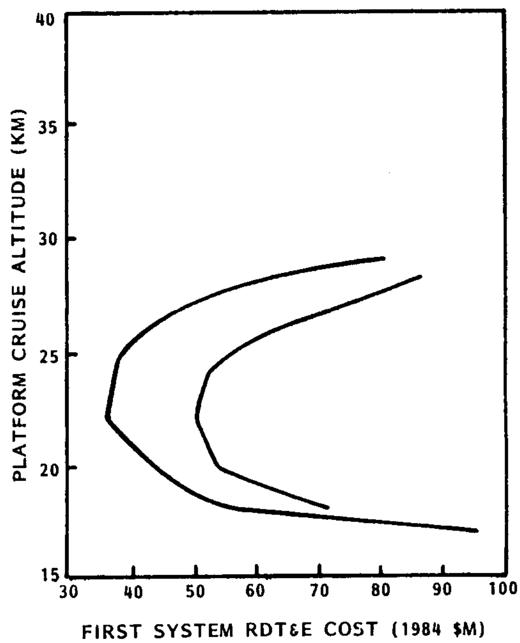


Figure 71B. Effect of Altitude Variations on First System RDT&E Cost for a Solid State Array and a Wing Rectenna

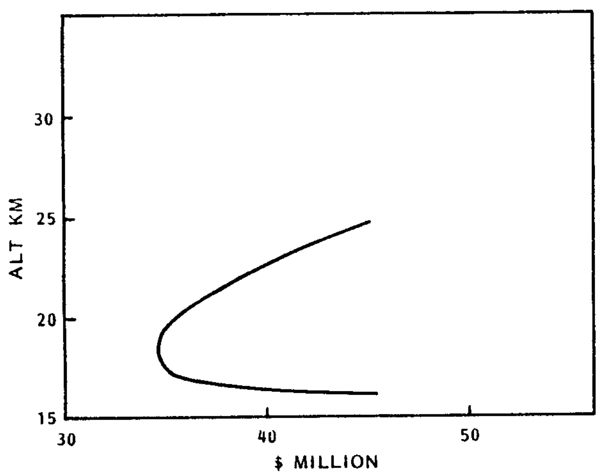


Figure 72A. Effect of Altitude Variations on First System RDT&E Cost for an 11 Meter Dish Array and a Disk Rectenna

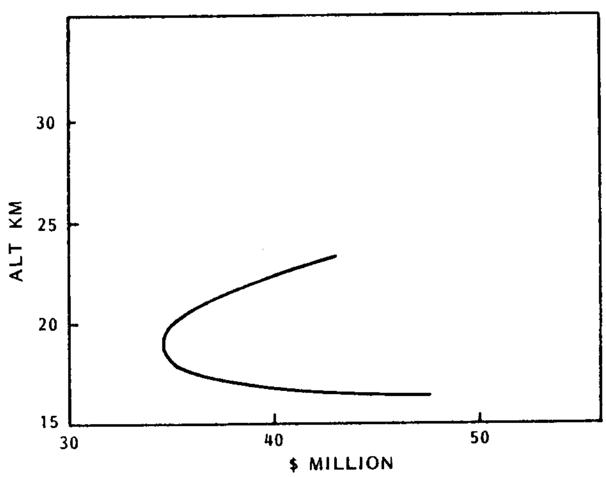


Figure 72B Effect of Altitude Variations on First System RDT&E Cost for an 11 Meter Dish Array and a Wing Rectenna

Lockheed

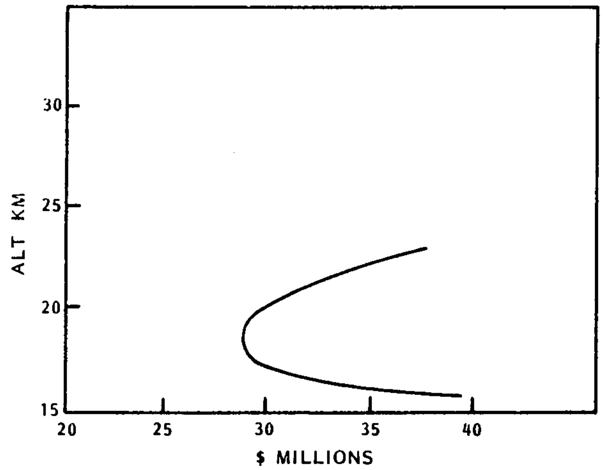


Figure 73A. Effect of Altitude Variations on First System RDT&E Cost for a 4.5 Meter Dish Array and a Disk Rectenna

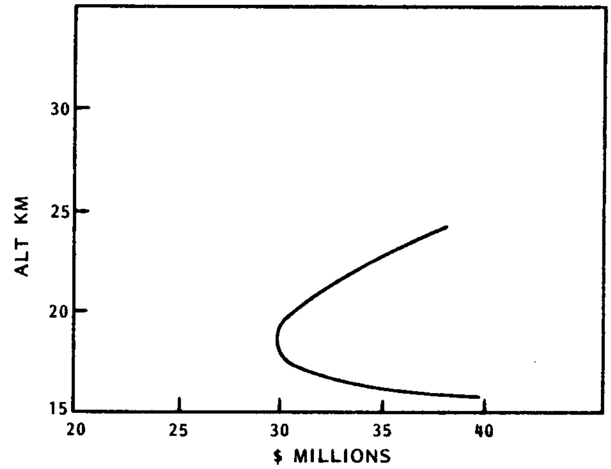


Figure 73B. Effect of Altitude Variations on First System RDT&E Cost for a 4.5 Meter Dish Array and a Wing Rectenna

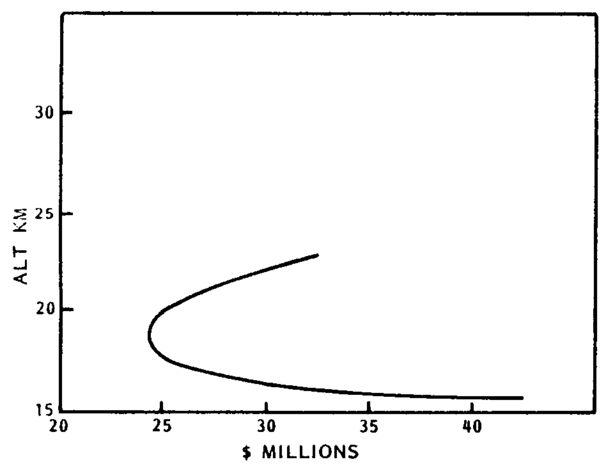


Figure 74A. Effect of Altitude Variations on First System RDT&E Cost for a Flat Slotted Array on Pedestals and a Disk Rectenna

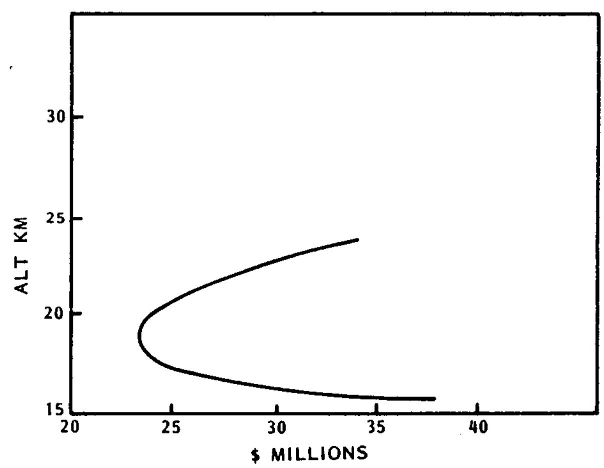


Figure 74B. Effect of Altitude Variations on First System RDT&E Cost for a Flat Slotted Array on Pedestals and a Wing Rectenna watts of power. Tradeoffs performed during this study have identified two system configurations which provide minimum first system RDT&E cost. Both use flat slotted ground arrays. The first is with the array mounted on the ground and the second is with the array mounted on pedestals. Total costs are close enough that either a conventionally configured platform or a joined wing platform could be used. Cruise altitudes in both cases are 20 and 19 km (65 600 and 62 320 feet),respectively and airspeed is 50 mps (97 kts). Total first system RDT&E cost will be under $20 M for both systems. If the original cost guideline of $30M is invoked, then system type 7, a ground array with 4.5 meter dishes and a platform with a disk rectenna, qualifies for inclusion. Table 39 presents these alternatives.

System Flexibilities

The systems described above are capable of operation over all six sites described in earlier sections because their cruise airspeeds and design altitudes are greater than 99th percentile winds aloft which may be expected at all sites.

Not examined during this study were:

- o Interface Problems and Solutions; and
- o System Reliability.

TABLE 39. THREE RECOMMENDED CO-OP SYSTEMS

SYSTEM TYPE	ALTI- TUDE KM	AIR- SPEED MPS	SPAN M	PLATFORM AR	PLATFORM TOGM KG	S_{REF} SQM	L/D	S_{RECT} SQM	PFD W/SQM	GROUND AREA SQM	GROUND POWER MW	TOTAL COST $M
Conventionally Configured Platform/Joined Wing												
1	20	50	44	21	778	92	29	55	450	3025	2.5	20.8
7	20	50	48	21	842	110	28	66	412	6082	1.1	29.5
10	19	50	40	14	785	114	25	69	424	4072	1.2	23.5

9.0 OPERATIONS AND MAINTENANCE

9.1 Overview

This section discusses the installation, operations and maintenance of a CO-OP System. Information is presented in terms of mission phases; that is, the facilities, equipment, tasks and operations are discussed in relation to the part they play in each mission phase. Mission phases are:

- Site preparation;
- Check-out;
- Pre-launch;
- Launch;
- Cruise;
- Descent;
- Landing;
- Post-flight; and
- Site removal.

This initial work establishes the outline to which study participants will add information about facilities, equipment and operations including number of personnel, skills required and any other information critical to the accomplishment of the mission. As such information is developed during the course of the study, these work sheets will be used to formulate a comprehensive mission timeline.

9.2 Mission Timeline

The timeline discussed in this section outlines the installation, operations and maintenance of a CO-OP System. Information is presented in terms of mission phases; that is, the facilities, equipment, tasks and operations are discussed in relation to the part they play in each mission phase.

- Site preparation;
- Check-out;
- Pre-launch;
- Launch;
- Cruise;
- Descent;
- Landing;
- Post-flight; and
- Site removal.

The timeline overview is based on detail worksheets for each phase that shares the facilities, equipment and operations including number of personnel, skills required and any other information critical to the accomplishment of the mission.

Preflight Phases

Site Preparation Ground Transmitter Subsystem. The ground transmitter site requires a level, cleared area approximately 100 meters (328 feet) in diameter, clear of trees and utility poles to at least another 10 meters (33 feet) around the periphery. The site should also be 0.5 kilometers (0.3 miles) or more from high voltage transmission lines. Concrete footings will be required for approximately 30 transmitting elements. The surface will be graded to provide for rain run-off. A building of approximately 50 square meters (500 square feet) will be required to house standard microwave test equipment needed to install and check out the transmitter. Initial installation of each transmitting element is expected to require four technicians and around 20 hours.

Site Preparation--Airstrip. An airstrip will be required close enough to the ground transmitter that the CO-OPS platform subsystem can be towed aloft into the transmitter beam. A hangar will be necessary to protect the CO-OPS platform from environmental conditions and to perform check-out. Because of the probable size of the CO-OPS platform and other logistical considerations, it may be advisable to airlift it to the airstrip. Therefore, runway requirements may be established by airlifter performance.

Check-out Phase--Ground Subsystem. Check-out of the ground subsystem--transmitter, power distribution and phasing equipment--will require three engineers and an estimated ten days. This operation will be accomplished by sections, with several elements per section, by running a twelve-hour shift for ten consecutive days.

Check-out Phase--Platform Subsystem. All platform subsystems will be checked out and certified ready for the pre-launch phase.

Pre-launch Phase. All equipment has been checked out at this point. This phase includes final flight clearances, chase plane and ground equipment preparation and, finally, moving the aircraft to launch position. Details of the actions will be more meaningful once technical information about the equipment to be used is available.

Launch Phase. The launch phase has two parts--takeoff and climb. Climb is divided into three segments:

- Towed climb to the minimum altitude to intersect the microwave beam;
- Powered climb in the microwave beam through positive control airspace; and

- o Powered climb in the microwave beam to operating altitude of (18.3 to 24.4 kilometers) 60 000 to 80 000 feet.

The chase plane will stay with the CO-OPS platform up to 5.6 km (18 500 feet).

Day-to-Day Operational Considerations

Flight Paths and Profiles. Sufficient work has been done by others (Ref.s 7 and Liu) in this area that it can be applied to the CO-OPS platform at the pre-Phase A level of detail. Later studies will apply specific CO-OPS mission payload needs to determine optimum flight paths.

Operational Limits Microwave Power Loop. On the ground an engineer will monitor tracking and power functions. Data from the platform will be collected in a small computer, organized and fed into automatic go-no go monitors. In addition, specific tests of input power to microwave power conversion will be made to decide when maintenance of the ground transmitter is needed. For maintenance, a transmitter unit will be taken off-line and another substituted.

Safety Limits. Platform operational safety limits were not examined during this study. The platform will be designed to be within the required design safety limits of the Federal Aviation Regulations for sailplanes.

Descent and Recovery

Descent Phase. Normal descent at the conclusion of the mission will be an orderly process in two segments. Descent will first be made to 5.6 kM (18,500 fat). This will be followed by descent through positive control airspace with a chase plane. Emergency descent,because of platform or ground subsystem failure, will be discussed in terms of specific incidents after candidate configurations and their performance parameters are known more completely.

Landing Phase. Recovery vehicles will be placed near the runway. The platform subsystem will be flown by remote control with emergency power, if possible, until it is necessary to index the propeller for a dead-stick landing.

Post-Flight Phase The platform will be taken to a hangar and ground or in fine tuning the ground system operations.
payloads will be removed and replaced. After checking for structural fatigue and examining the outerskin for ultraviolet degradation, the platform will be made ready for another mission. If necessary, a new payload may be installed.

Site Removal Phase. The CO-OP System will be designed to facilitate relocation to another operating site. Equipment will be disassembled, packed for shipment and transported to a new location. It is estimated that the second installation of the ground subsystem can be accomplished in about one-half the time required for the first installation.

9.3 Scheduled Maintenance

In operation, the airborne component is powered and controlled by the microwave beam. Maintenance is implemented by automatic monitoring of system operation for both the airplane subsystems and the data sensor system. All critical functions will be monitored and go-no-go tests will be applied to each parameter. A no-go signal will energize an analysis and alerting system on the ground. Built-in logic, excited by no-go signals, will initiate specific tests in the airborne component and also recall previously recorded data on the ground. These data will be used to establish the state of the system.

The status and parameter values of some functions and conditions such as temperature of the power components, the microwave environment in the sensor bay and structural aeroelasticity will be transmitted to the ground station for storage and data processing. These data will be processed to determine trends. Trending can be used to vary operating conditions by modifying control and/or power functions from the ground or in fine tuning the ground system operations.

9.4 Summary of System O & M Requirements

Estimates of the maintenance requirements have been made for each of the candidate ground power systems. The basis for these estimates was extrapolations from Raytheon's extensive experience with large aperture arrays. Included are system of similar magnitude and similar scope like PAVE PAWS and COBRA DANE both with over 10K array elements and also the ROTHR, an over the horizon radar requiring a comparable amount of real estate to that needed by the CO-OPS.

A summary of the maintenance cost estimates for all candidates is given in Table 40. A more detailed maintenance breakdown of two candidates the cooker magnetron/slotted array and the 40KW Klystron/11M dish antenna is given in Tables 41 and 42. In arriving at these estimates it was assumed that the ground system would be designed to incorporate built in test with remote reporting. A central reporting station would be used to inform the operator of needed maintenance. Replacement of LRU's would be performed on a scheduled basis rather than an immediate one. Because the number of ground systems is large, particularly in the case of the slotted array, the ground system can tolerate about 10% of the antenna transmitter sets failing before it becomes necessary to begin replacement. What this means with respect to the manpower needed to perform the maintenance can be less than that needed to handle a possible peak load and that the availability of the ground system could be 100% during the 2-3 month operational flight period.

Repair of failed components that have been replaced in the system will be returned to point of manufacture or to a central depot for evaluation and repair. Because of the tolerance of large arrays to failures the level of spares that need to be kept at the site can be less than 10% providing there are more than one system in the field.

TABLE 40. MAINTENANCE COST SUMMARY

CANDIDATE	MAINTENANCE COST YR.
COOKER MAGNETRON/SLOTTED ARRAY (500W)	$ .8M
COOKER MAGNETRON/SLOTTED ARRAY ON PEDESTAL	$1.5M
IND HEAT MAG/11M DISH FEED STEERED (5KW)	$1.2M
30 KW KLYSTRON/11M DISH FEED STEERED	$1.2M
30 KW KLYSTRON/11M DISH PEDESTAL STEERED	$1.5M

TABLE 41. CO-OPS SYSTEM STUDY

11M DISH ON PEDESTAL

SYSTEM	COMPONENT	MAINTENANCE
ANTENNA	DISH	NONE
	PEDESTAL	NONE
	CONTROLLER	REPAIRS AS REQUIRED
	DRIVE MOTOR	REPAIRS AS REQUIRED
TRANSMITTER	KLYSTRON	REPAIRS AS REQUIRED - 2 MEN REPAIR
	HIVOLTAGE POWER SUPPLY	REPAIRS AS REQUIRED
CONTROL SYSTEM		
MANPOWER REQUIRED	2/SHIFT	3SHIFTS/DAY 7 TOTAL

MANPOWER MAINTENANCE COST $1.5M/YR

TABLE 42. SLOTTED ARRAY ON PEDESTAL

SYSTEM	SYSTEM COMPONENT	MAINTENANCE
ANTENNA	ARRAY	CLEAN RADOME CLEAN DRAINAGE
TRANSMITTER	MAGNETRON ASSEMBLY	NONE GRACEFUL DEGRADATION REPLACE FAILURE TIME TO REPAIR 15 MINUTES
	PRIMARY POWER	REPAIR SHORTS AND RESET BREAKERS
CONTROL SYSTEM	COMPUTER	REDUNDANT
	DOWN LINK	REDUNDANT
	UPLINK	REDUNDANT
	DATA STORAGE	REDUNDANT
MANPOWER REQUIRED	1/shift 3 shift/DAY	5 TOTAL
MANPOWER MAINTENANCE COST	800 K/YR	

RECTENNA

The rectenna reliability is almost entirely determined by the microwave power conversion diodes it uses. The diode reliability is controlled by its operating temperature which in turn is controlled by the microwave power input to the diodes and the cooling design. The latter is expected to be radiant and convection. It is further anticipated that if the microwave power is kept to less than 8 watts per diode or equivalently to less than 1000 watts/square meter the cooling design could be simple convection.

Refurbishment of the rectenna will not be necessary until about 18% of the diodes have failed. The expected time for this to happen is in excess of 20,000 hours thereby reducing the need for any rectenna maintenance.

Because the antenna is critical in supporting the CO-OPS mission it will be necessary to monitor its operation during the flight to assure that minimum output power is available from the rectenna to support the mission. Monitor data will be telemetered to the ground along with scientific data. There it is expected that an operator or computer will analyze the data.

If the analysis indicates that the power density is reaching a critical level which could accelerate diode failure the operator will take action to reduce the level through the ground power system power control system. If, on the other hand, the power output of the rectenna is below that required to support flight and the payload, the flight will be aborted. After its return to the ground the rectenna will be removed and replaced with a spare. Since the rectenna is expected to fail gracefully, the time to replace can be predicted and the aircraft brought down while there is sufficient power to support. Since the rectenna is expected to fail gracefully there is no need to keep a spare at the site.

DATA SUBSYSTEM

The communications portion of the data subsystem will be designed with completely redundant airborne components and with critical component redundancy in the ground portion of the Data Subsystem. The overall MTBF is expected to be in the order of 20000 hours. Maintenance, when required, would be performed by replacing the failed component. Component units are for the most part off the shelf production units. All failed units would be sent back to the original manufacturer for repair. For temporal zone installations, spares for the Data Subsystem as well as all other ground power elements, can be central depotted. However, an arctic installation poses transportation problems. It would probably be advisable to have all spares physically on location instead of at a central depot.

10.0 CONCLUDING REMARKS

10.1 Viable Systems and I.O.C. Options

After extensive parametric analyses using the system sizing methodology described earlier in this report, several viable CO-OP Systems have been identified. These will be summarized here by subsystem .

Ground Subsystems

Ground Antennas and Power Transmitters. Platforms were sized with specific ground antenna and power transmitter options which are presented in Table 43.

If subsystem mobility is considered a mission requirement,cost of the ground subsystem will increase. Table 44 presents the changes in costs of both a Reflector array and a slotted array if mobility is considered. This table above presents time and costs to move each type of ground subsystem once. It has been assumed that transportation costs to another site would be the same whether the subsystem is fixed or mobile. As an example of transportation cost level, an array made up of 100-11M dishes on pedestals could be loaded aboard a USAF/Lockheed C-141 transport and flown to McMurdo Sound in the antarctic for around $25M. As the chart points out, slotted arrays may be designed for mobility from the outset for a modest increase in subsystem cost; therefore, if mobility is a consideration, slotted arrays may be the more suitable alternative.

Platform Subsystems

Several platform subsystems appear viable for use in a CO-OP System. Presented in Table 45 are ten platforms with indications of size, mass, cost and development readiness. Cruise airspeed used is 50 meters per second (97 knots) at altitudes from 19 to 21 km (62 to 70 kfeet) and payload mass is 270 kg (595 lbf).

In addition to these platform subsystems which were sized for moderately high-altitude operation, a platform was sized for operation at an altitude of 37km (121 kfeet). This platform would have a wingspan of 110m (361 feet) with a total system RDT&E cost of between $200M and $300M in 1984 dollars.

Feasible Combinations of Ground and Platform Subsystems

Table 46 presents combinations of platform and ground subsystems which yield the least expensive options. Also shown are an indication of development readiness and total first system RDT&E cost in 1984 dollars.

TABLE 43. VIABLE GROUNDPOWER SUBSYSTEM OPTIONS

	SUBSYSTEM	INPUT POWER MW	DIA OR SIDE-M	MASS Kg	COST (1984 $M)	DEVELOPMENT READINESS
A.	SLOTTED ARRAY ON PEDESTALS - WITH MAGNETRONS	1.15	72 DIA	50,000	15.34	EXC - GOOD
B.	SLOTTED ARRAY FLAT - WITH MAGNETRONS	2.49	55 x 55	93,800	12.46	EXC - GOOD
C.	4.5M DISH WITH MAGNETRONS	1.28	93 DIA	93,500	22.95	EXC - GOOD
D.	11M DISH WITH KLYSTRONS	1.29	96 DIA	114,700	27.5	GOOD
E.	SLOTTED ARRAY WITH	1.35	85 X 85	31.100	33.51	FAIR SOLID-STATE

TABLE 44. COST OF SUBSYSTEM MOBILITY

ANTENNA TYPE	ITEM	FIXED SUBSYSTEM	MOBILE SUBSYSTEM	MOBILITY COST
SLOTTED ARRAY X 65M 65M	DESIGN/PRODUCTION/ ASSEMBLY	$12M	$13.0M	
	DISASSEMBLY	1M	0.5M	
	TOTAL	$13M	$13.5M	$0.5M
	DISASSEMBLY TIME	1-2 MONTHS	1-1.5 MONTHS	
	REASSEMBLY TIME	2-3 MONTHS	2-3.0 MONTHS	
REFLECTORS 11M DIAMETER	DESIGN/PRODUCTION/ ASSEMBLY	$17M	$48M	
	DISASSEMBLY	3M	1M	
	TOTAL	$20M	$49M	$29.0M
	DISASSEMBLY TIME	2-3 MONTHS	1/2-1.0 MONTHS	
	REASSEMBLY TIME	2-3 MONTHS	1-2 MONTHS	

TABLE 45. VIABLE PLATFORM SUBSYSTEM OPTIONS

RECTENNA	GROSS MASS	WING-SPAN	ASPECT RATIO	FLUX DENSITY REQUIRED	COST (1984$M)	DEVELOPMENT READINESS
WING WITH D	698KG	34M	14	510W/SQM	7.29	
WING WITH C	683KG	36M	16	490W/SQM	7.30	
DISK WITH D	755KG	40M	19	494W/SQM	7.94	
WING WITH A	785KG	40M	14	424W/SQM	8.16	SEE NOTE
DISK WITH B	778KG	44M	21	405W/SQM	8.32	
WING WITH E	807KG	40M	13	406W/SQM	8.33	
WING WITH B	821KG	42M	14	405W/SQM	8.54	
DISK WITH C	842KG	48M	21	411W/SQM	8.98	
DISK WITH E	858KG	50M	22	401W/SQM	9.23	
DISK WITH A	872KG	50M	22	419W/SQM	9.32	

NOTE: All platforms utilize state-of-the-art technology and manufacturing, therefore the development readiness of all ten configurations is considered excellent.

TABLE 46. VIABLE COMBINATIONS OF GROUND AND PLATFORM SUBSYSTEMS

	PLATFORM SUBSYSTEM	RECTENNA MOUNT	ANTENNA TYPE	POWER TRANSMITTER	DEVELOPMENT READINESS	1st SYSTEM RDT&E ($M)
1.		DISK	SLOTTED ARRAY	MAGNETRONS	EXCELLENT	20.8
2.		WING	SLOTTED ARRAY	MAGNETRONS	EXCELLENT	21.0
3.	NOTE: WOLKOVITCH	WING	SLOTTED ARRAY ON PEDESTALS	MAGNETRONS	EXCELLENT	23.5
4.	JOINED- WINGS OR CONVEN- TIONAL	DISK	SLOTTED ARRAY ON PEDESTALS	MAGNETRONS	EXCELLENT	24.6
5.	CANTI- LIVERED WINGS ARE APPLICABLE	DISK	4.5 M DISHES	KLYSTRON	EXCELLENT	29.5
6.	TO ALL TEN CONFIGUR-	WING	4.5M DISHES	KLYSTRON	EXCELLENT	30.24
7.	ATIONS.	WING	11M DISHES	KLYSTRON	EXCELLENT-GOOD	34.8
8.		DISK	11M	KLYSTRON	EXCELLENT-GOOD	35.4
9.		DISK	SLOTTED ARRAY	SOLID-STATE	GOOD	37.2
10.		WING	SLOTTED ARRAY	SOLID-STATE	GOOD	41.8

NOTE: THE MINIMUM COST SYSTEM ($20.8M) RESULTED FROM COMBINING THE MINIMUM COST GROUND SUBSYSTEM B, (TABLE 43 @ $12.46M) WITH PLATFORM SUBSYSTEM, "DISK WITH B" (TABLE 45 @ $8.32M).

Altitude Options

Various altitude options were examined during the course of this study, from 6 to 40 km (19 680 to 131 200 feet) and with All of these systems are capable of performing missions carrying the smaller payload. Above 24 km (78 720 feet), system cost begins to increase markedly as shown by Figure 75 below.

Payload Subsystems

Site 1 and 5 Initial Payload and Site 2,3,4 Additional Payload. Based on mission/site/ODR tradeoffs, the instrument complement listed in Table 47 below would permit satisfaction of almost all of the ODRs. Assuming a hierarchical approach to acquisition of the instruments, the complement for initial Site #1 observations would consist of some subset of the listed instruments. Planning by users active in these fields of research is required to select the best instruments. This complement would also satisfy the ODRs for Site #5. The addition of two instruments to this complement, the CZCS or OCI ocean spectral imager and the ALT altimeter, would permit satisfaction of the ODRs for all the additional sites discussed here.

Further desired instrumentation, Table 48 below, lists instruments that would be needed to satisfy the remaining ODRs. In addition, an assortment of in-situ monitors should be included on the platform and some ground based monitors should be included in the mission.

Key interface parameters of the potential payload complement for the prototype verification test site are summarized in Table 49. A total of ten instruments will be required to meet ODR sensing requirements over the site. This package will probably weigh 270 kilograms (595 lbf) and might require a total of 185 watts of power during their duty cycles.

The initial payload may be some subset of these instruments along with some ground-based sensors and some in-situ sensors. Later payloads could evolve by adding and deleting instruments as observational requirements and budgets dictate. The advanced solid-state array spectroradiometer (ASAS) is an example of an existing sensor. Such instrumentation, if it can be acquired, could provide a low cost initial payload.

To summarize, instrumentation identified during this study meets nearly all of the ODRs using level I (currently available) instrumentation. Atmospheric CO_2 (ODR 2), vertical cloud structure (ODR 7), and atmospheric surface pressure (ODR 18) require additional instrumentation. Ground-based instruments may be useful for the later ODR.

10.2 Issues Requiring Further Consideration

Figure 76 lists some of the uncertainties identified during this study relative to payloads. The space-borne CO_2 temperature sounding technique,

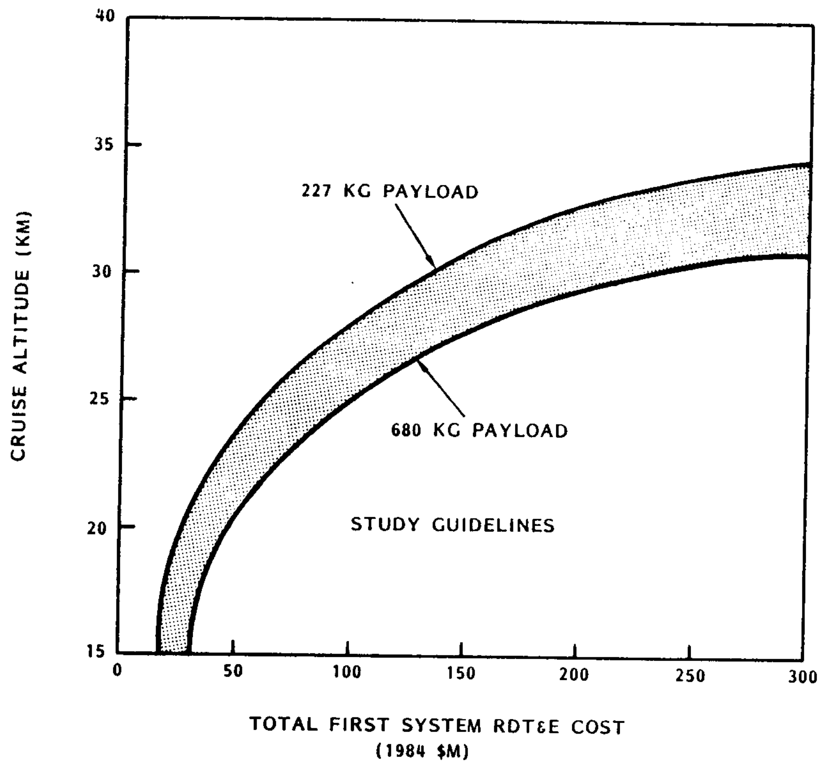


Figure 75. Variation of First System RDT&E Cost with Operational Altitude

TABLE 47. SUMMARY OF INSTRUMENT COMPLEMENTS

INSTRUMENT	INSTRUMENT CAPABILITY
HIRS-2 (HIGH RESOLUTION INFRARED SOUNDER-2)	TEMPERATURE SOUNDING AND WATER VAPOR PROFILE
AVHRR-2 (ADVANCED VERY HIGH RESOLUTION RADIOMETER-2)	VISIBLE, NIR, IR IMAGING RADIOMETER
SAGE-2 (STRATOSPHERIC AEROSOL AND GAS EXPERIMENT-2)	AEROSOL AND GAS MEASUREMENT AT LIMB
SMMR (SCANNING MULTI-CHANNEL MICROWAVE RADIOMETER)	HUMIDITY SOUNDING ICE AND WIND
SBUV/TOMS (SOLAR BACKSCATTER ULTRAVIOLET RADIOMETER-TOTAL OZONE MAPPING SPECTROMETER)	OZONE PROFILE UV SOLAR IRRADIANCE
ERBE (EARTH RADIATION BUDGET EXPERIMENT)	
NON-SCANNER	SOLAR OUTPUT
SCANNER	EARTH RADIATION IN THREE BANDS: -TOTAL (0.2 TO 50 MICROMETERS) -SHORT WAVE (0.2 TO 5 MICROMETERS) -LONG WAVE (5 TO 50 MICROMETERS)
SCAT (SCATTEROMETER)	WIND FIELD, BOTH SPEED AND DIRECTION
ASAS (ADVANCED SOLID-STATE ARRAY SPECTRORADIOMETER)	SILICON CHARGE-COUPLED DEVICE PUSHBROOM IMAGING SPECTRORADIOMETER
THIR (TEMPERATURE, HUMIDITY INFRARED RADIOMETER)	IMAGING TEMPERATURE AND HUMIDITY RADIOMETER CLOUDS, WATER VAPOR
ADDITIONS FOR SITES # 2,3 AND 4	
ALT (ALTIMETER)	RADAR ALTIMETER
CZCS/OCI (COASTAL ZONE COLOR SCANNER/OCEAN COLOR IMAGER)	OCEAN SURFACE CHARACTERISTICS SURFACE TEMPERATURE

TABLE 48. FURTHER DESIRED INSTRUMENTATION

INSTRUMENT	ADDED CAPABILITY
ATMOS, LASER HETERODYNE SPECTROMETER OR LIMB SCANNING SPECTROMETER	CARBON DIOXIDE AND TRACE GASES (ODR 2,3)
PARALLAX SENSOR	CLOUD VERTICAL STRUCTURE (ODR 7)
IN-SITU MONITORS ON PLATFORM	TEMPERATURE PRESSURE WIND VELOCITY GAS AND AEROSOL SAMPLING PARTICLE CONCENTRATIONS
GROUND BASED MONITORS	SOLAR FLUX MONITOR PLATFORM ALTITUDE, ORIENTATION, DIRECTION OF FLIGHT, SPEED AIR PRESSURE

TABLE 49. POTENTIAL PAYLOAD COMPLEMENT FOR THE PROTOTYPE VERIFICATION TEST SITE

CATEGORY	INSTRUMENT	MASS	POWER
Remote Sensing	HIRS-2	32.3KG	22.8W
	AVHRR-2	28.7KG	26.2W
	SAGE-2	29.5KG	14.0W
	SMMR	52.5KG	60.0W
	SBUV	35.0KG	
	TOMS	31.0KG	12.0W
	ASAS		
	ERBE		
	SCANNER	29.0KG	
	NON-SCANNER	32.0KG	50.0W
TOTAL		270.0KG	185.0W
In-Situ	CONTAMINATION		
	TEMPERATURE		
	PRESSURE		
	WIND VELOCITY		
	GAS SAMPLING		
	AEROSOL SAMPLING		
	PARTICLE CONTAMINATION		
Ground-Based Sensors	RADIOSONDE		
	SOLAR FLUX		
	TEMPERATURE		
	PRESSURE		

SCIENCE OBJECTIVES:
● ODR # 2: ATMOSPHERIC CO_2 CONCENTRATION ● ODR # 7: CLOUDS, VERTICAL STRUCTURE ● ODR # 18: SURFACE ATMOSPHERIC PRESSURE ● SUITABILITY OF CO_2 TEMPERATURE SOUNDING TECHNIQUE FROM 20 KM ● IN-SITU SENSORS--DEFINITION OF GROUND-BASED SENSORS
QUANTITATIVE PERFORMANCE ASSESSMENT INTERFACE WITH PLATFORM:
● VIEWING CONSTRAINTS ● DRAG ● CONTAMINATION ● MASS ● DATA LINK ● POWER
EFFECT OF ATMOSPHERE ON OI'S:
● O_3 ● H_2O ● ETC
AVAILABILITY OF HARDWARE

Figure 76. CO-OPS Payload Subsystem Uncertainties

when applied at the low altitudes considered here (around 20 kM), may not be suitable. Other items which need definition are:

- o A quantitative performance assessment of the instruments from the platform altitude of 20 kM (65 600 feet);
- o Payload/platform interface including operational constraints;
- o Long-term effect of the environment at altitude on the instruments;

10.3 Other Applications (Task 10)

Analyses done during this study have shown that the CO-OP System will be capable of operating at all six sites specified in the guidelines for this study. Other sites may be accommodated as long as their local winds aloft profiles are similar to those examined here.

In addition, a wide variety of payloads may be carried which weigh in the vicinity of 300 kg (660 lbf) without markedly changing the sizing of the CO-OPS platform. This mass figure should accommodate payloads for all of the ancillary missions described at the beginning of this report. Payload power levels can be approximately 1kw before affecting platform design.

Capabilities of State-of-the Art Components

The tasks required to develop a baseline design for payload accommodations during the forthcoming Phase A of the CO-OPS Study have been identified. The following are key tasks to be studied:

- o Determine required modifications for up to ten existing instruments. The modifications required will be determined to a level of fidelity required to assess interface, performance and cost.
- o Define standard payload/platform mechanical, electrical, thermal, optical and cryogenic interfaces which are compatible with the derived platform.
- o Estimate the radiometric and imagery performance of up to ten existing instruments while mounted on the platform.
- o Define typical operational sequences for up to ten instruments.
- o Assess the effect of the microwave environment on the instruments and recommend design and operational controls.
- o Assess the contamination control issues and recommend design and operational controls.

- Assess the availability and cost of up to ten selected instruments.

10.4 Recommendations (Task 9)

The contractor team which performed this study has unanimously concluded that the CO-OP System concept is feasible within the technology, schedule and cost guidelines given at the start of this study. The required technologies of payload sensors, microwave transmitters and receivers, platform capabilities and data handling have all been demonstrated separately and can be combined synergistically to accomplish the CO-OP System prototype goals before 1990 and within present cost limitations.

We therefore recommend two primary systems which were numbers 1 and 3 of Table 46. These systems provide the following benefits:

- Systems 1 and 3 represent state-of-the-art systems with excellent development readiness characteristics and lowest cost of the alternatives examined here;

- Platforms 1 and 3 will provide tradeoff information between a joined wing and a conventional configuration;

- Rectennas 1 and 3, disk- and wing-mounted, will permit the evaluation and determination of the relative merits of both;

- Ground power subsystems 1 and 3, either a flat slotted array on pedestals or on the ground, will primarily be evaluated for the beam steering capability of each;

- System 5 will be investigated to the extent necessary to evaluate the operational advantages and disadvantages of antenna dishes and klystron power transmitters since 1 and 3 contain neither of these subsystem components. While this system is 35% more costly than the others, its costs are still within the study guideline and, therefore, should not be abandoned before further analysis in Phase A.

Lockheed is prepared to immediately initiate further planning activities with NASA/Marshall Space Flight Center, the Department of Energy and the scientific user community in order to ensure the timely and systematic progress of the CO-OPS program through Phases A through D and into productive and cost effective operations.

REFERENCES

1. Glaser, Peter E. and Vranka, Robert, "System Study of the Utilization of Space for Carbon Dioxide Research", NASA Marshall Space Flight Center, CR 3923, October 1985.

2. Lory, Fred J., "HI-SPOT Conceptual Design Study Final Report", Lockheed Missiles and Space Company Contract N62269-81-C-0276 with Naval Air Development Center, March 1982.

3. Brown, William C., "Design Study for a Ground Microwave Power Transmission System for Use with a high-altitude Powered Platform", NASA CR-168344, 1983.

4. Jull, Dr. G.W.,Lillemark, A., and Turner, R.M., "SHARP (Stationary high-altitude Relay Platform): Telecommunications Missions and Systems", Canadian Department of Communications, Communications Research Centre, Ottawa, to be presented at IEEE Globecom Conference, New Orleans, Louisiana, December, 1985.

5. DeLaurier, J., Gagnon, B., Wong, J., Williams, R., and Hayball, C., "Research on the Technology of an Airplane Concept for a Stationary high-Altitude Relay Platform (SHARP)", Institute for Aerospace Studies, University of Toronto, Presented at the 32nd Annual Meeting of the Canadian Aeronautics and Space Institute, Montreal, Canada, May 27, 1985.

6. Jull, Dr. G.W., "Summary Report on SHARP (Stationary high-altitude Relay Platform), Part A- Technical Feasibility of Microwave-Powered Airplanes", Canadian Department of Communications, Communications Research Centre, Ottawa, September, 1985.

7. Reynaud, A.H., and Martin, J.F., "Airplane Concept for Stationary High Altitude Relay Platform (SHARP)", CASI Remotely Piloted Vehicles Symposium, Montreal, Canada, May 27, 1985.

8. Wolkovitch, Julian, "The Joined Wing: An Overview", AIAA 23rd Aerospace Sciences Meeting Paper # AIAA-85-0274, Reno, Nevada, January 14-17, 1985.

9. Vaughan, Otha H., "Atmospheric Research from a Long Endurance aircraft", presented to the 2nd Annual high-altitude Long Endurance aircraft Symposium, Menlo Park, California, October 1985 and Unmanned Vehicle Systems Magazine, Association for Unmanned Vehicle Systems, Winter 1986.

10. Kuhner, Mark B., "Applications of a high-altitude Powered Platform", American Institute of Aeronautics and Astronautics, 1979.

11. Kuhner, Mark B. and McDowell, Jack R., "User Definition and Mission Requirements for Unmanned Airborne Platforms (Revised)", NASA Contractor Report 156861, 1979.

12. Hall, David W., Fortenbach, Charles D., Dimiceli, Emanuel D., and Parks, Robert W., "A Preliminary Study of Solar Powered aircraft and Associated Power Trains", NASA Langley Research Center, Contractor Report 3699, 1983.

13. Hall, David W., Watson, David A., and Tuttle, Robert W.,"Mission Analysis of a Solar-Powered aircraft", NASA Langley Research Center, Contractor Report 172583, 1985.

14. Brewer, G. Daniel, et.al.,"High-Altitude Configuration Technology Volume 1-Program Results", AFWAL-TR-83-3097, Volume 1, 1983.

15. Morris, Charles E.K., "Design Study for Remotely Piloted, High-Altitude Airplanes Powered by Microwave Energy", AIAA Applied Aerodynamics Conference, July 13-15, 1983, Danvers, Massachusetts (AIAA-83-1825).

16. Heyson, Harry H., "Initial Feasibility Study of a Microwave-Powered Sailplane as a High-Altitude Observation Platform", NASA Langley Research Center, Technical Memorandum # 78809, December, 1978.

17. Boucher, R. J. "Project Semrise", presented to the Joint Propulsion Conference of AIAA/SAE/ASME, June 1979 (AIAA 79-1264)

18. Jackson, Ray D., "Plant Health; A View From Above", from "Challenging Problems in Plant Health," edited by T. Kommedahl and P. Williams, The American Phytopathplogical Society, 1983.

19. Strganac, Thomas W., "Wind Study for high-altitude Platform Design", NASA Wallops Flight Center RP-1044, 1979.

20. Smith, Robert E. and West, George S., "Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development, 1982 Revision (Volume 1)", NASA Marshall Space FLight Center, TM 82478, 1983.

21. Turner, Robert E. and Hill, C. Kelly, "Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1982 Revision", NASA Marshall Space Flight Center, TM 82473, 1982.

22. Hall, David W. and Hall, Stanley A., "Structural Sizing of a Solar Powered aircraft", NASA Contractor Report 172313, April, 1984.

23. Stefan, Karl, "Concept for a Long Endurance high-altitude Airship", presented to the 2nd Annual high-altitude Long Endurance aircraft Symposium, Menlo Park, California, October 31, 1985.

24. Hale, Francis J., Introduction to Aircraft Performance, Selection and Design, John Wiley & Sons, Inc., New York, 1984.

25. Nicolai, Leland M., "Fundamentals of aircraft Design", University of Dayton Press, 1975.

26. Stephens, J. Briscoe, "Potential Spin-Offs of the Carbon Dioxide Observation Platform System (CO-OPS) for Remote Sensing Opportunities", NASA Marshall Space Flight Center Technical Paper, June 17, 1985.

27. Nicholson, Lt. Cdr. Craig M., "Coast Guard C3", Signal, May/June, 1982.

28. Wood, K.D., "Aerospace Vehicle Design, Volume I, Aircraft Design", Johnson Publishing Company, Boulder, Colorado 1968.

29. Brown, William C., "A Profile of Power Transmission by Microwaves", AIAA Astronautics and Aeronautics, May, 1979.

30. Sinko, James W., "Circling Flight in Wind for HAPP aircraft", NASATechnical Note SED-716, August 25, 1978.

31. Larrabee. E. Eugene, "Design of Propellers for Motorsoarers", Massachusetts Institute of Technology, 1978.

32. Marcy, W.L. and Hookway, R.O., "Propulsion Options for the HI-SPOT Long Endurance Drone Airship", prepared for Naval Air Development Center by Martin Marietta Corporation (Report MCR 79-632), 15 September 1979.

33. Wolkovitch, J., "Joined-Wing Research Airplane Feasibility Study", AIAA-84-2471 prepared for the AIAA/AHS/ASEE aircraft Design Systems and Operations Meeting, October 31-November 2, 1984.

34. Anonymous, "High Surveillance Platform for Over-the-Horizon Targeting (HI-SPOT) Study", prepared for NAval Air Development Center (Contract Number N62269-81-C-0277) by Teledyne-Ryan Aeronautical, 27 February 1982.

35. Liu, Grace C., Morris, Jr., Charles E.K. and Koenig, Robert W., "Performance of High-Altitude, Long-Endurance, Turboprop Airplanes Using Conventional or Cryogenic Fuels", NASA Langley Research Center, 1980.

36. Benstein, Eli, "Very Long Endurance Flight with Gas Turbine Power", Unmanned Systems, Winter 1985.

37. Jones, S.P. and DeLaurier, J.D., "Aerodynamic Estimation Techniques for Aerostats and Airships", AIAA Journal of aircraft, February 1983.

38. Brown, William C., "The History of Power Transmission by Radio Waves", IEEE Transactions on Microwave Theory and Techniques, September 1984.

39. Fordyce, Samuel W. and Brown, William C., "Applications of Free-Space Microwave Power Transmission", AIAA Journal of aircraft, 1979.

40. Frequency Allocations-Manual of Regulations and Procedures for Federal Radio Frequency Management- p.6 Revision 5/82, U.S. Department of Commerce NTIA.

APPENDIX A CO-OPS OBSERVATIONAL DATA REQUIREMENTS

The preliminary guidelines for the DOE CO-OPS observational data measurement requirements will be summarized in terms of: (1) the candidate categories of CO-OPS observational data requirements, and (2) a list of candidate geographical CO-OPS operation sites. The basis for these requirements is taken from the NASA/MSFC system study of the utilization of space for carbon dioxide research for the DOE Carbon Dioxide Research Program prepared under contract and documented in the following final report:

> Glaser, P.E.; and R. Vranka: System study of the utilization of space for carbon dioxide research. Prepared for NASA/Marshall Space Flight Center by Arthur D. Little, Inc. in association with Ball Aerospace Systems Division, Boeing Aerospace Company on contract NAS8-35357, April 1984.

This report addresses the global observational data objectives and requirements of the DOE Carbon Dioxide Research Program; however, this MSFC CO-OPS prephase A system study will address the regional observational data objectives and requirements of the DOE Carbon Dioxide Research Program. The global observational data requirements were defined in terms of the "modeling database" for global circulation models utilized in the DOE Carbon Dioxide Research Program. Based on DOE requirements, the "modeling database" was refined by DOE to reflect the CO-OPS preliminary "observational data requirements" they desired. DOE also provides a list of Candidate Geographical CO-OPS Operation Sites with the observational data requirements for each site.

To review and summarize, the ADL study identified the following space observable data requirements:

Lockheed

SDR NO.	SPACE DATA REQUIREMENTS	GRID SIZE (km)	TEMPORAL SAMPLING (Days)	ACCURACY
1.	AEROSOL CONCENTRATION	1000	30	10%
2.	ATMOSPHERIC CONCENTRATIONS, CARBON DIOXIDE	500	3	1 ppa
3.	ATMOSPHERIC CONCENTRATIONS, TRACE GASES	1000	30	0.5 ppa
4.	BIOSPHERE, VEGETATION INDEX	200	30	--
5.	CLOUDS, CIRRUS	200	1	--
6.	CLOUDS, FRACTIONAL COVERAGE	200	0.5 hr	5%
7.	CLOUDS, VERTICAL STRUCTURE	200	0.5 hr	0.5
8.	LAND ICE	--	365	1 a el
9.	PRECIPITATION	200	1	10%
10.	RADIANCE AT THE TOP OF THE ATMOSPHERE	1000	1	0.1-5%
11.	SEA CURRENTS	200	30	2-5 ca
12.	SEA ICE	200	5	1%
13.	SEA LEVEL	200	30	10 ca
14.	SEA SURFACE TEMPERATURE	200	5	0.2°
15.	SEA SURFACE WINDS	100	30	2 a/sec
16.	SNOW COVER	200	5	5%
17.	SURFACE ALBEDO	200	30	2%
18.	SURFACE ATMOSPHERIC PRESSURE	500	30	1.5 ab
19.	SURFACE MOISTURE, SOIL	500	30	10%
20.	SURFACE TEMPERATURE, SOIL	500	30	1°C
21.	VERTICAL TEMPERATURE	500	5	1-2°C
22.	VERTICAL WATER VAPOR PROFILE	200	2	10%
23.	WIND FIELD	500	.5	0.3% a/sec

As stated previously, the objective of this study is the conceptual design of a high-altitude observational platform system that can meet the guidelines for the data measurement requirements for the DOE Carbon Dioxide Research Program. To achieve this objective, it is necessary to determine as many of the DOE requirements as possible for: (1) the categories of CO-OPS observational data requirements in terms of the scientific data requirements and (2) a list of geographical CO-OPS operation sites with the appropriate categories of CO-OPS observational data requirements.

I. Candidate Categories of CO-OPS
Observational Data Requirements

Category A. ATMOSPHERIC PROFILES

SDR No.	MODELING DATA BASE: Observational Data Requirements	OBSERVATIONAL DATA BASE: Grid Size (km)	Temporal Sampling (Days)	Accuracy	Grid Size	Temporal Sampling	Accuracy
21.	VERTICAL TEMPERATURE PROFILE	500	5	1-2°C	150	4 hrs	0.2°C
	<u>DOE Comments:</u>						
22.	VERTICAL WATER VAPOR PROFILE	500	5	10%	150	4 hrs	5 - 10%
	<u>DOE Comments:</u>						
23.	WIND FIELD	500	.5	0.3 a/sec	150	4 hr	0.1 a/sec
	<u>DOE Comments:</u>						

I. Candidate Categories of CO-OPS
Observational Data Requirements
(Cont.)

Category B. ATMOSPHERIC SPECIES

SDR No.	Observational Data Requirements	MODELING DATA BASE Grid Size (km)	Temporal Sampling (Days)	Accuracy	OBSERVATIONAL DATA BASE Grid Size (km)	Temporal Sampling (days)	Accuracy
1.	AEROSOL CONCENTRATION	500	30	10%	150	4 hrs	5%
DOE Comments:							
2.	ATMOSPHERIC CONCENTRATIONS, CARBON DIOXIDE	500	3	1 ppa	10-100	LOCAL Noon & Midnight	0.3 ppb
DOE Comments:							
ODR	On Platform Measurements:						
A.	TEMPERATURE, PRESSURE, & WIND VELOCITY GAS & AEROSOL SAMPLING				LOCAL	Hourly	State-of the-art
DOE Comments:							
B.	PARTICLE CONCENTRATIONS				LOCAL	Hourly	State-of the-art

Lockheed

I. **Candidate Categories of CO-OPS**
Observational Data Requirements
(Cont.)

Category C. CLOUDS

SDR No.	Observational Data Requirements	MODELING DATA BASE Grid Size (km)	MODELING DATA BASE Temporal Sampling (days)	MODELING DATA BASE Accuracy	OBSERVATIONAL DATA BASE Grid Size (km)	OBSERVATIONAL DATA BASE Temporal Sampling (days)	OBSERVATIONAL DATA BASE Accuracy
5.	CLOUDS, CIRRUS DOE Comments: Cloud top & bottom temperatures and altitudes are desired.	200	1 hr	--	1.0	20 min	0.5°C
6.	CLOUDS, FRACTIONAL COVERAGE DOE Comments:	200	0.5 hr	5%	200	20 min	5%
7.	CLOUDS, VERTICAL STRUCTURE DOE Comments: Measurements should include: a. Ice content b. Water content c. Precipitation d. Rate precipitation (/hour) e. Altitude of top & bottom of clouds f. Temperature structure of clouds	200	1.0 hr	5%	0.5	10 min	TBD
10.	RADIANCE AT TOP OF THE ATMOSPHERE DOE Comments:	500	1	0.1-5%	TBD	TBD	TBD

I. Candidate Categories of CO-OPS Observational Data Requirements (Cont.)

Category D. SEA/OCEAN

SDR No.	Observational Data Requirements	Modeling Data Base: Grid Size (km)	Modeling Data Base: Temporal Sampling (days)	Modeling Data Base: Accuracy	Observational Data Base: Grid Size (km)	Observational Data Base: Temporal Sampling (days)	Observational Data Base: Accuracy
11.	SEA CURRENTS DOE Comments:	200	30	2-5 ca	10	0.5	TBD
12.	SEA ICE DOE Comments:	200	5	1%	10	0.5	TBD
13.	SEA LEVEL DOE Comments:	200	30	1 ca	10	0.5	TBD
14.	SEA SURFACE TEMPERATURE DOE Comments:	200	5	0.2°C	10	0.5	TBD
15.	SEA SURFACE WINDS DOE Comments:	100	30	2 a/sec	10	0.5	TBD

I. Candidate Categories of CO-OPS Observational Data Requirements (Cont.)

Category E. SNOW/ICE

SRD No.	Observational Data Requirements	MODELING DATA BASE Grid Size (km)	Temporal Sampling (days)	Accuracy	OBSERVATIONAL DATA BASE Grid Size (km)	Temporal Sampling (days)	Accuracy
8.	LAND ICE	--	365	1 a elev	100	7	TBD
	DOE Comments:						
16.	SNOW COVER	200	5	5%	100	1	TBD
	DOE Comments:						

I. Candidate Categories of CO-OPS
Observational Data Requirements
(Cont.)

Category F. SURFACE CONDITIONS

SDR No.	Observational Data Requirements	MODELING DATA BASE Grid Size (km)	MODELING DATA BASE Temporal Sampling (days)	MODELING DATA BASE Accuracy	OBSERVATIONAL DATA BASE Grid Size (km)	OBSERVATIONAL DATA BASE Temporal Sampling (days)	OBSERVATIONAL DATA BASE Accuracy
9.	PRECIPITATION DOE Comments: Which clouds. At what rate and total amount.	200	1	10%	10	0.25	5%
17.	SURFACE ALBEDO DOE Comments:	200	30	2%	100	1	1%
18.	SURFACE ATMOSPHERIC PRESSURE DOE Comments:	500	30	1.5 ab	500	1	1 ab
19.	SURFACE MOISTURE, SOIL DOE Comments:	500	30	10%	100	7	5%
20.	SURFACE TEMPERATURE, SOIL	500	30	$1^{o}C$	100	7	$0.5^{o}C$

APPENDIX B. CO-OPS OBSERVATIONAL DATA REQUIREMENTS

II. Candidate Geographical CO-OPS Operation Sites

The preliminary guidelines for the DOE CO-OPS observational data measurement sites will be summarized. It must be emphasized that CO-OPS should be designed to be a quasi-mobile system that can be moved to new sites as the DOE Carbon Dioxide Research Program requires. This area will require careful consideration by DOE.

CO-OPS Operational Site No. 1: **NASA/MSFC**

The initial CO-OPS operational site will be at NASA/MSFC

OBSERVATIONAL REQUIREMENTS

Observational Categories	Altitude (km)	Observation Time
A, B, C, & F	20	TBD

DOE Comments:

CO-OPS Operational Site No. 2: **VAFB/EAFB**

The next site of operation will be probably Vandenberg/Edwards Air Force Base.

CO-OPS Operational Site No. 3: East Coast

OBSERVATIONAL REQUIREMENTS

Observational Categories	Altitude (km)	Observation Time
A, B, C, D, & F	20	TBD

DOE Comments:

CO-OPS Operational Site No. 4: Other Sites

Other potential sites for long-term CO-OPS include, but are not limited to, the West Antarctic, the Intertropical Zone (e.g. Panama) and an east coast site at about 60° North latitude.

OBSERVATIONAL REQUIREMENTS

Observational Categories	Altitude (km)	Observation Time
A, B, C, D, E, & F	20	TBD

DOE Comments:

Lockheed

CO-OPS Operational Site No. 5: Target of Opportunities

Other operation sites will include targets of opportunity such as areas associated with volcanic activity.

OBSERVATIONAL REQUIREMENTS

Observational Categories	Altitude (km)	Observation ^{0} Time
A, B, C, & F	6 - 40	Hourly

DOE Comments:

a. Emphasis should be placed on ODR A in Category B.

b. Explore the feasibility of the use of drop and up sondes.

U.S. GOVERNMENT PRINTING OFFICE: 1988 - 530-050/80012